perfection

SEVENTH FRAMEWORK PROGRAMME

PERFECTION – Performance Indicators for Health, Comfort and Safety of the Indoor Environment

FP7 Grant Number 212998

# *T1.3 Performance Indicators for Health and Comfort*

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# CONTENTS

# 1. INTRODUCTION

Regarding PERFECTION work package 1, it is the objective to investigate current performance indicators, standards, regulations, guidelines, research activities and policies used in design and construction of the built environment. While subtask 1.3 focuses on performance indicators for health and comfort (indoor environmental quality), subtask 1.4 focuses on accessibility, feeling of safety and positive simulation indicators. It is the intention of the project to develop an overall framework for building performance indicators integrated within a sustainable built environment.

This report presents a review of the health and comfort indicators for indoor environment in buildings. It is the objective to provide an overview and a complete list of performance indicators for health and comfort, which can be applicable in a performance indicator framework for the assessment of building performance.

The specific objective related to Subtask 1.3 is to provide a review of health and comfort related to acoustic comfort, visual comfort, indoor air quality, quality of drinking water, and thermal comfort. The indicators are reviewed focusing on the implementation in an indicator framework for building performance assessment.

First of all, a summary of the earlier work, mainly within EU-projects, on performance based building and performance indicators for the indoor environment is presented. Second, the Performance Based Building (PBB) concept and definitions of terms applied within the context are described. After a discussion of the definitions, performance indicators related to the indoor environment are reviewed. An analysis of existing and missing indicators has been performed.

# 2. PERFORMANCE CONCEPT

The basic concept of Performance Based Building (PBB) and its methodology has already been described in 1982 in the CIB-Report 64 (CIB 1982) [1]. The concept is summarized as:

1. The performance approach is thinking and working in terms of ends rather than means.
2. Performance is concerned with what a building or building product is required to do and not with prescribing how it is to be constructed.

The main difference between PBB and the (generally) traditional practice therefore is that with PBB the requirements are all posed in terms of performance in-use instead of required and therefore prescribed solutions that are assumed to adhere to the posed needs, based on practical experience (guidelines). This means that solutions are provided for by the supplier (e.g. design team, manufacturer) and they will have to include the estimated performance of that solution in response to the requirement.

In addition to the above two statements that define PBB, a third one therefore should be included to complete the definition:

3. A design solution, traditional or novel, will always need a quantitative base for testing and evaluation of its performance.

The Nordic Model was one of the first models to be developed that adhered to the performance concept. An adapted version of the model is shown in Figure 1. In this adapted version the 'Compare & Match' layer is positioned in between the 'Why & What' and the 'How'. In the original version the 'How' layer was not included and deemed-to-satisfy solutions were positioned parallel to the verification layer. This original model, for example, has formed the base for the development of the Dutch building decree, which has a performance based approach. However, in this building decree no acceptable solutions are presented.

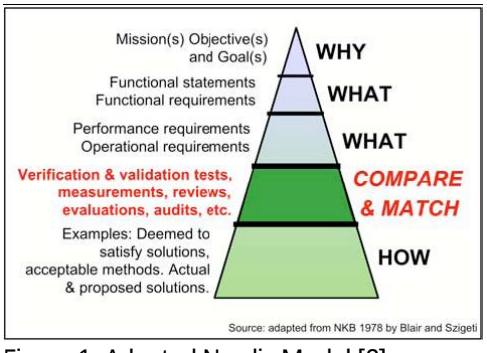



Figure 1: Adapted Nordic Model [2]

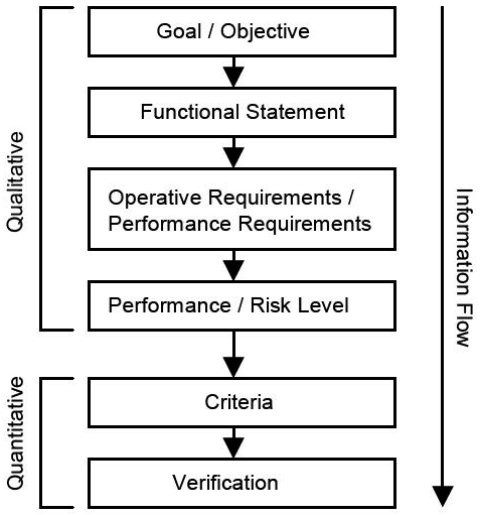



Figure 2: Performance System Model

The CIB Task group 37 'Performance based building regulatory systems' developed a model to analyse and describe the various systems of performance based requirements [3]. The

Performance System Model (PSM; Figure 2) expands the upper levels of the Nordic Model, introducing a 'Performance/Risk level', which translates the requirements to relevant (key) indicators for which performance should be assessed. In the level 'Criteria' target values are quantified for these indicators. The 'Verification' level focuses on the 'Compare&Match' level of the Adapted Nordic Model and does not explicitly address the solution part.

The key characteristics of the Performance concept are defined by Szigeti and Davis (2005) [2]. The concept requires two languages. On the one hand, there is a requirement (demand) and, on the other hand, there is a capability to meet that demand and perform as required (supply). Conceptually, the dialog between client and supplier can also be expressed as two halves of a hamburger bun, with the statement of the requirement in functional or performance language matched to a solution in more technical language, and the matching, verification/validation that needs to occur in between (Figure 3).

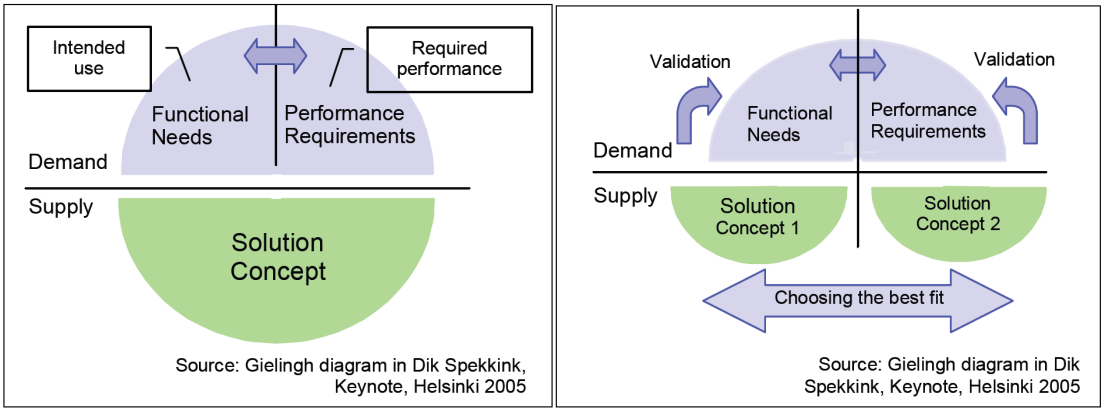


Figure 3: Hamburger model [4]

Ang, Groosman, and Scholten (2005) [5] describe the Hamburger Model as follows: The functional concept (FC) represents the set of unquantified objectives and goals to be satisfied, related to performance requirements to fulfil these needs. The solution concept (SC) represents the technical materialisation that satisfies at least the required performance. The development or selection of a solution concept is a design decision. The assumed or actual realisation allows for the determination of expected or real performance. This performance differs in general from the required performance and shall be at least equal to the required performance.

They continue: A validation method, by measurement, calculation, or testing, is necessary to evaluate the performance and to compare alternative solutions. Systematic decomposition creates a coherent set of performance requirements and technical solutions with appropriate validation methods. The structure of an object is being described by decomposition and the pertaining set of performance requirements and verification methods is developed and organized. Figure 4 visualises the above description. Performance therefore can/needs to be assessed at different levels (from building material/product to integrated whole building performance). Within Perfection focus will be on the higher (integral) levels, implicitly resulting in performance requirements for building components, products, etc.

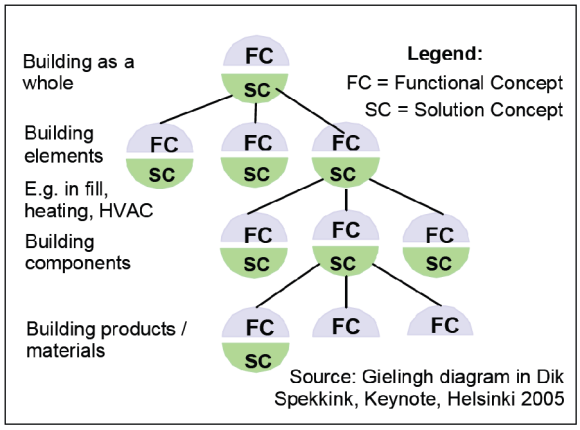



Figure 4: Decomposition of the requirements for evaluation at different functional levels.

Evaluation, validation and verification reveal whether the solution concept actually fulfils the requirements set in the functional concept. This assessment can be done in many ways. The physical measurements of, e.g. performance indicators of building products, is relatively straightforward and has already a long history. This is laid down in numerous testing guidelines (e.g. ISO or ASTM standards). More global assessments, e.g. at building component, building element or building level is less straightforward. Besides testing, reviews, audits and questionnaires can provide approaches for these types of assessments in the construction and use phase. For the design phase other evaluation tools are required. Rules-of-thumb, reference cases and building simulations tools, with different levels of complexity, are examples of such tools.

This leads to the filled Hamburger model as shown in Figure 5. It is a model that can be applied at any point in the building life, from initiation to demolition.

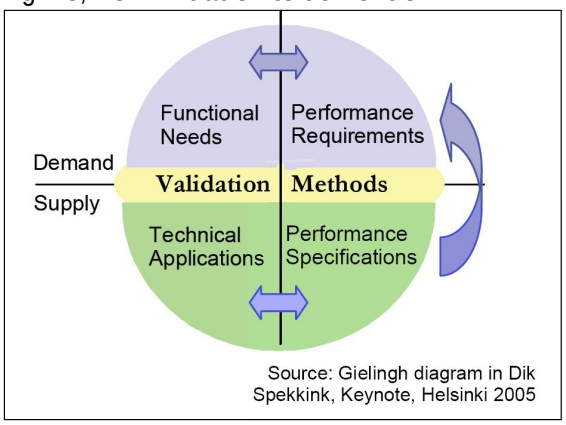
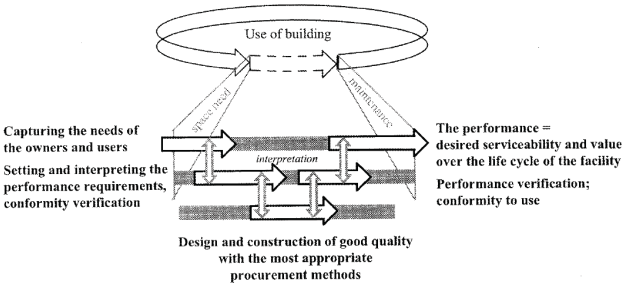



Figure 5: filled Hamburger model [4].



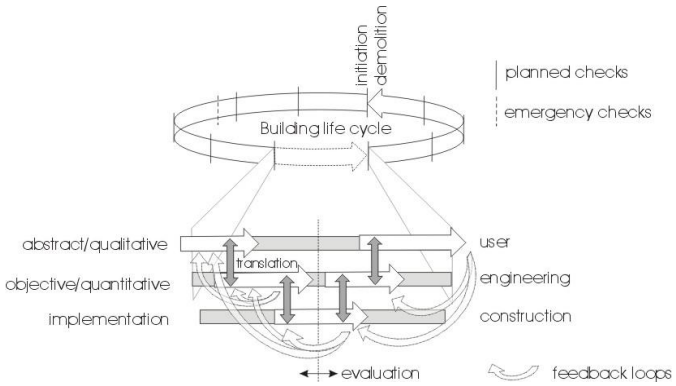



Figure 6: Definition of performance based approach [6] [7]

Figure 6 visualises an extended definition of the performance based approach, which includes the principle of the Hamburger model and its decomposition [7]. It was adapted from a figure by Huovila and Leinonen [6]. The figure shows that the concept of performance based building does not end with the completion of the building, but is a function of time (includes also changes in performance requirements). It furthermore states that performance can only be assessed in a specific context, of which the stakeholder, the building phase and a building object are the main parameters. As an example, the user wants to live comfortably in the building, whereas the contractor is interested in the performance of individual building objects to obey to the design plan. Figure 6 also introduces the translation of functional requirements into performance requirements and the actual design and evaluation of that. This translation will build on, for instance, legislation, experience, rules-of-thumb and modelling.

## 2.1. Individual definitions

Though the overall definition of the performance based approach can be captured in three sentences, capturing the essence of these sentences has shown not to be straightforward. Also the definitions for the terminology used in this description are not always unambiguous in literature.

Some overviews of definitions can be found in Szigeti et al. (2005) [2], Deru and Porcellini (2005) [8] and Loomans and Bluyssen (2005) [7], but they are not in full agreement. Recently an ISO/TC 59 document [9] came available that also defines several terms.

With respect to the term 'performance indicator' the following (related) definitions were found:

*Indicator*:
- quantitative, qualitative or descriptive measure [9]
- a variable which helps to measure a state or a progress towards an objective [10]

*Core Indicator*:
- Defines an essential aspect of a building with respect to a specific topic (e.g. sustainability; [9])

*Performance Metric*:
- a standard definition of a measurable quantity that indicates some aspect of performance [8]

*Performance Indicator*:
- a high-level performance metric that is used to simplify complex information and point to the general state or trends of a phenomenon [8]

- Properties of a product, building component or a building that closely reflects or characterise its performance in relation to the performance requirement that has been set. The indicator should be a quantifiable parameter that can be readily calculated or measured [7]

Following a discussion in the Perfection Prague Meeting (June 2009) the final definition was agreed on as follows:
*Core Indicator*:

- Defines an essential aspect of a building with respect to a specific topic (e.g. sustainability; [9]). To be defined by one or a set of performance indicators.

*Performance Indicator*:

- Property of a product, building component or building, which closely reflects or characterises its performance (state or progress towards an objective) in relation to the performance requirement that has been set. The indicator should be a quantitative, qualitative or descriptive parameter that can be readily assessed.

*Set of indicators*:

- Non-structured list of indicators.

Below definitions are given based on the information provided by the references and in line with the overall definition as presented above. In Loomans and Bluyssen (2005) [7] some additional definitions are given for other terms.

*Objective/Goal*
Addresses the essential interests of the community at large with respect to the built environment and/or needs of the individual user-consumer.

*Merriam Webster: Objective - something toward which effort is directed: an aim, goal, or end of action*

*Example: Obtaining a constructed asset portfolio that fits the company's long-term goals (e.g. growth, products, …).*

*Functional requirement*
Building or building specific requirements that address a specific aspect or required performance of the building to achieve the stated goal.

*Example: A building to perform office work with low energy use and a productive indoor environment.*

*Performance requirement*
Outlines a suitable level of performance which must be met by building materials, components, building as a whole in order for a building to meet the relevant functional statements and, in turn, the relevant objectives. The requirement can be assessed by an objective assessment method.

*Example: The indoor environment of the office should agree to the highest level of the Finnish Indoor Climate Classification System.*

*Performance indicator*
Property of a product, building component or building, which closely reflects or characterises its performance (state or progress towards an objective) in relation to the performance requirement that has been set. The indicator should be a quantitative, qualitative or descriptive parameter that can be readily assessed.

*Example: The PMV value is an indicator for the assessment of thermal comfort.*

*Target value*
Quantified value (range) for the performance indicator in order to adhere to the performance requirement set.

*Example: The PMV-value should be with -0.5 and 0.5 for 90% of the time over the whole year.*

*Physical attributes*
(With respect to the indoor environment) the physical, chemical, biological and physiological parameters that relate to the performance indicator and that have to be registered in order to determine the performance indicator.

*Example: In order to determine the PMV value, the air temperature, mean radiant temperature, air velocity and relative humidity have to be measured, in combination with identified (or agreed on) values for the clothing resistance and metabolic rate.*

In summary, a general definition of a (core) performance indicator has been presented. It was demonstrated that a core performance indicator can be described by a set of indicators or parameters. Each indicator or parameter can be assessed qualitatively or quantitatively. Target values describe specific guidelines with respect to each indicator/parameter. The analysis proceeds with a review of the performance indicators for the acoustic comfort, visual comfort, indoor air quality, quality of drinking water, and thermal comfort in a building. For each performance indicator, specific indicators, parameters, and target values are presented.

# 3. ACOUSTIC COMFORT

Noise effects resulting from outside and inside sources may have an adverse influence on occupants' comfort as well as on their intellectual and physical performance. The typical indicator of acoustic comfort is the level of acoustic pressure. Moreover, acoustic comfort can also be assessed on the basis of users' satisfaction. A literature study has been carried out to investigate the state-of-the-art on the assessment of the acoustic comfort in a building. International standards, building regulations and research presented in scientific papers have been analyzed. In this section, the performance indicators describing the acoustic comfort in a building are presented. The performance indicators and parameters are characterized and categorized.

## 3.1. Acoustic performance

The overall objective of the performance indicators regarding the acoustic comfort in a room is to provide acoustic conditions in a building that facilitate clear communication of speech between the users of the building. Performance indicators on the following topics are specified in this section to achieve this objective:

- indoor ambient noise levels
- airborne sound insulation between spaces
- airborne sound insulation between corridors or stairwells and other spaces
- impact sound insulation of floors
- reverberation
- speech intelligibility

### 3.1.1. Indoor ambient noise levels in unoccupied spaces

In a building, suitable indoor ambient noise levels for clear communication are required. The indoor ambient noise level includes noise contributions from:

- External sources outside the building (including, but not limited to, noise from road, rail and air traffic, industrial and commercial premises)
- Building services (e.g. ventilation system, plant, etc). If a room is naturally ventilated, the ventilators or windows should be assumed to be open as required to provide adequate ventilation. If a room is mechanically ventilated, the plant should be assumed to be running at its maximum operating duty.

The indoor ambient noise level excludes noise contributions from:

- Activities within the building, including noise from users and equipment within the building. Noise transmitted from adjacent spaces is addressed by the airborne and impact sound insulation requirements.
- Equipment used in the space (e.g. machine tools, CNC machines, dust and fume extract equipment, compressors, computers, overhead projectors, fume cupboards). However, these noise sources should be considered in the design process.
- Rain noise.

Generally, upper limits for the indoor ambient noise levels for each type of unoccupied space are defined. The noise levels are specified in terms of $L_{Aeq,30min}$, which is the average noise level

over 30 minutes. The specified levels refer to the highest equivalent continuous A-weighted sound pressure level, $L_{Aeq,30min}$, likely to occur during normal working hours. The levels due to external sources will depend on weather conditions, e.g. wind direction, and local activities. High noise levels due to exceptional events may be disregarded.

The indoor ambient noise levels apply to finished but unoccupied and unfurnished spaces. Tonal and intermittent noises are generally more disruptive than other types of noise at the same level. Noise from plant, machinery and equipment in noise–sensitive rooms should therefore be constant in nature and should not contain any significant tonal or intermittent characteristics. Noise from building services which is discontinuous, tonal, or impulsive, i.e. noise which can be distracting, should be reduced to a level at least 5 dB below the specified maximum.

### 3.1.2. Airborne sound insulation between spaces

The objective is to attenuate airborne sound transmitted between spaces through walls and floors. The required minimum airborne sound insulation values between rooms are generally defined by the activity noise in the source room and the noise tolerance in the receiving room. The activity noise and noise tolerance for each type of room are defined by the Building Regulations [11]. The airborne sound insulation is quoted in terms of the weighted standardized level difference, $D_{nT(Tmf,max)w}$, between two rooms. The standardized level difference, $D_{nT(Tmf,max)}$, is the level difference, in decibels, corresponding to a reference value of the reverberation time in the receiving room:

$$D_{nT\,(Tmf\,,\max)} = D + \lg\left(\frac{T}{T_{mf\,,\max}}\right)$$

Where $D$ is the level difference [dB], $T$ is the reverberation time in the receiving room [s], $T_{mf,max}$ is the reference reverberation time equal to the upper limit of the reverberation time, $T_{mf}$, for the type of receiving room. This reference reverberation time shall be used for all frequency bands.
The standardized level difference, $D_{nT(Tmf,max)}$, is measured in accordance with ISO standard 140/IV [12] in octave or one-third octave bands, the results are weighted and expressed as a single-number quantity, $D_{nT(Tmf,max)w}$, in accordance with ISO standard 717/I [13]. The prediction and measurement of $D_{nT(Tmf,max)w}$, between two rooms must be carried out in both directions as its value depends upon the volume of the receiving room.

### 3.1.3. Airborne sound insulation between circulation spaces and other spaces

The attenuation of airborne sound transmitted between circulation spaces (e.g. corridors, stairwells) and other spaces is described by the required minimum airborne sound insulation for the separating construction. The airborne sound insulation for walls and doorsets is quoted in terms of the weighted sound reduction index, $R_w$, which is measured in the laboratory. The airborne sound insulation for ventilators is quoted in terms of the weighted element-normalized level difference, $D_{n,e,w}$. The performance standard for ventilators is quoted in terms of $D_{n,e,w}$ –10lg $N$ where $N$ is the number of ventilators with airborne sound insulation $D_{n,e,w}$. The weighted sound reduction index is measured in accordance with ISO standard 140/IV [12] and rated in accordance with ISO standard 717/I [13]. The weighted element-normalized level difference is measured and rated in accordance with ISO standard 717/I [13].

The performance standard is set using a laboratory measurement because of the difficulty in accurately measuring the airborne sound insulation between rooms and corridors, or rooms and stairwells in the field. Therefore it is crucial that the airborne sound insulation of the wall and/or doorset is not compromised by flanking sound transmission, e.g. sound transmission across the junction between the ceiling and the corridor wall.

### 3.1.4. Impact sound insulation of floors

The impact sound (e.g. footsteps) transmitted into spaces via the floor is limited by the recommended maximum weighted standardized impact sound pressure level, $L'_{nT(Tmf,max)w}$, for receiving rooms of different types and uses. The standardized impact sound pressure level, $L'_{nT(Tmf,max)}$, is the impact sound pressure level in decibels corresponding to a reference value of the reverberation time in the receiving room:

$$L'_{nT(Tmf,\max)} = L_i - 10\lg\frac{T}{Tmf,\max}$$

where $L_i$ is the impact sound pressure level (dB), $T$ is the reverberation time in the receiving room (s), $T_{mf,max}$ is the reference reverberation time equal to the upper limit of the reverberation time, $T_{mf}$ , for the type of receiving room. This reference reverberation time shall be used for all frequency bands. The standardized impact sound pressure level, $L'_{nT(Tmf,max)}$, is measured in accordance with ISO Standard 140/VII [14] in octave or one-third octave bands, the results are weighted and expressed as a single-number quantity, $L'_{nT(Tmf,max),w}$, in accordance with [15]. Impact sound insulation should be designed and measured for floors without a soft covering (e.g. carpet, foam backed vinyl) except in the case of concrete structural floor bases where the soft covering is an integral part of the floor.

### 3.1.5. Reverberation

The reverberation time of a room used to be regarded as the predominant indicator of its acoustic properties. The reverberation time, *T* [s], of a room is defined as the time required for the sound pressure level to decrease by 60 dB, at a rate of decay given by the least-squares regression of the measured decay curve from a level of 5 dB below the initial level to 35 dB below the initial level. Whilst reverberation time continues to be regarded as a separate parameter, there is reasonable agreement that other types of measurements such as relative sound pressure levels, early energy ratios, lateral energy fractions, inter-aural cross correlation functions and background noise levels are needed for a more complete evaluation of acoustic quality of rooms.

Generally, the ISO Standard 3382 [16] is used to specify the acoustic quality of a room by the reverberation time based on the impulse response method. Additionally, the standard introduces two levels of complexity in room acoustic performance. Since the ISO Standard 3382 [16] provides an intensive description of the measurement of the reverberation time in a room regarding the measurement procedure, the equipment needed, the coverage required, and the data evaluation method, the reader is referred to the standard for additional information.
Suitable reverberation times are required for (a) clear communication of speech and (b) acoustic performance of the spaces in a building. The reverberation time is quoted in terms of the mid-frequency reverberation time, $T_{mf}$ , the arithmetic average of the reverberation times

in the 500 Hz, 1 kHz and 2 kHz octave bands. Additionally, Table 1 presents a second level of performance parameters describing the acoustic performance of a room. The table presents a short definition of the parameters. The quantities in the table are related to the clarity, or the balance between clarity and reverberation, as well as to speech intelligibility

Table 1: Performance parameters for acoustic performance

| Parameter | | Definition |
|---|---|---|
| $T_{30}$ | [s] | Reverberation time, derived from -5 to -35 dB of the decay curve |
| EDT | [s] | Early decay time, derived from 0 to -10 dB of the decay curve |
| D | [%] | Deutlichkeit (definition), early (0-50 ms) to energy ratio |
| C | [dB] | Clarity, early (0-80 ms) to late (80 ms to ∞) energy ratio |
| $T_s$ | [ms] | Centre time, time of 1. Moment of the energy impulse response |
| G | [dB] | Sound level related to omni-directional free-field radiation at 10m range |
| LF | [%] | Early lateral (5-80ms) energy ratio, i.e. the energy arriving within the first 80ms from lateral directions ($\cos^2$, lateral angle) |
| LFC | [%] | Early lateral (5-80ms) energy ratio (cos, lateral angle). |

### 3.1.6. Speech Intelligibility

Within a building, clear communication of speech between the users of the building should be provided. Large spaces, such as open plan spaces, require extra specification, as these may be more complex acoustic spaces. The main issue is that the noise from different groups of people functioning independently in the space may significantly increase the background noise level, and thus decrease speech intelligibility.

Large, open plan, spaces are generally designed for high flexibility in terms of the layout. In addition, the layout is rarely finalized before the building is operational, and this may increase the complexity of assessing the speech intelligibility. At an early stage in the design, the designer should establish the expected layout and activity plan with the client, including the positions of the building's users, the seating plan, and the specific activities.

The acoustic quality of a large room or open plan space is usually characterized by the speech intelligibility, which has attracted the attention of many researchers in the past many decades. Indices such as the speech transmission index (STI) [17], the articulation index [18], the percentage loss of consonants [19] and the useful-to-detrimental sound ratio ($U_{50}$) [20] are proposed for assessing the speech intelligibility in rooms. The results of Bradley [21] tend to suggest that these indices are highly correlated with each other, implying that they are in principle equivalent for the purpose. The speech intelligibility is affected by the background noise. Strong correlations between the STI or speech intelligibility scores with various acoustic parameters derived from the impulse response of a room have also been established (for instance [22]). These parameters include the reverberation times (RT), clarity or early/late energy ratio (C), definition (D), centre time ($T_s$) and $U_{50}$.

Moreover, balanced noise-criterion (NCB) curves [23] can be used to predict whether the noise in a space, measured in octave bands, will interfere with speech communication, i.e. whether the averages of the band levels in the frequency between 350 and 6000 Hz are low enough, and if so, whether relative to that average, individual band levels below and above 1000 Hz will be high enough to be annoying to occupants.
NCB curves were established in U.S. for rating indoor noise, noise from air-conditioning equipment etc. In Europe it is common to use Noise Rating (NR) Curves. The method consists

of a set of criteria curves extending from 63 to 8000 Hz, and a tangency rating procedure. The criteria curves define the limits of octave band spectra that must not be exceeded to meet occupant acceptance in certain spaces (Figure 7).
The NC rating can be obtained by plotting the octave band levels for a given noise spectrum - the NC curves. The noise spectrum is specified as having a NC rating same as the lowest NC curve which is not exceeded by the spectrum.

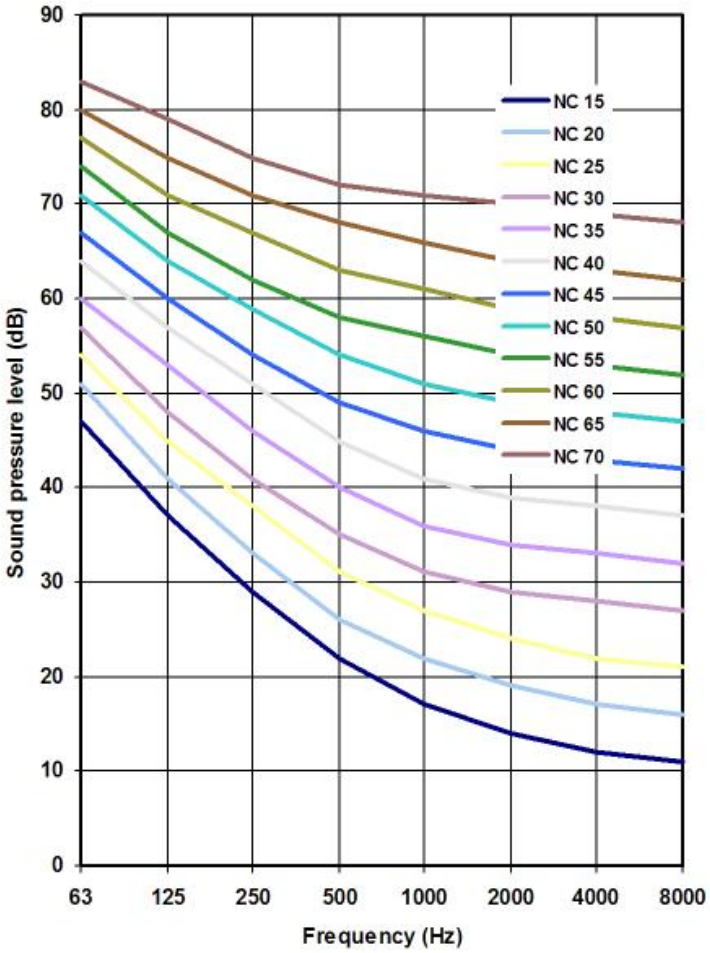



Figure 7: Noise-criterion (NC) or noise rating (NR) curves.

Table 2: Noise rating curves for different applications

| Noise criterion curve | Application |
|---|---|
| NC 25 | Concert halls, broadcasting and recording studios, churches |
| NC 30 | Private dwellings, hospitals, theatres, cinemas, conference rooms |
| NC 35 | Libraries, museums, court rooms, schools, executive offices |
| NC 40 | Halls, corridors, cloakrooms, restaurants, night clubs, offices, shops |
| NC 45 | Department stores, supermarkets, canteens, general offices |
| NC 50 | Typing pools, offices with business machines |
| NC 60 | Light engineering works |
| NC 70 | Foundries, heavy engineering works |

## 3.2. Structural vibrations at low frequencies

Structural vibration, between 1 and 80 Hz, to which human beings are exposed in buildings can be detected by the occupants and may affect them in many ways. More particularly, their comfort and quality of life may be reduced. The increase in low frequency sources outside and inside buildings has motivated both practical [24] [25] and theoretical evaluations of the sound transmission in buildings at low frequencies. Examples of sources include loudspeakers with enhanced bass response for hi-fis and home cinema systems [26]. Traffic and mechanical systems (ventilators, fuel burners and water coolers) have significant low-frequency components in their spectra [27].

The evaluation of vibration in buildings is presented in the standard ISO 2631 [28]. The standard concerns human exposure to whole body vibration and shock in buildings regarding comfort and annoyance of the occupants. A method for the measurement and evaluation, comprising the determination of the measurement direction and measurement location, is specified.

Experience in many countries has shown that adverse comments regarding building vibration in residential situations may arise from building occupants when the vibration magnitudes are only slightly in excess of perception levels. In some cases complaints arise due to secondary effects associated with vibration, e.g. reradiated noise. In general, satisfactory magnitudes are likely to be related to general expectations and to economic, social and other environmental factors. They are not determined by factors such as short-term health hazards and working efficiency. Indeed, in particularly all cases the magnitudes are such that fatigue directly induced by the motion is very unlikely.

### 3.2.1. Effects of vibrations on comfort and perception

A particular vibration condition may be considered to cause unacceptable discomfort in one situation but may be classified as pleasant or exhilarating in another. Many combined factors to determine the degree to which discomfort may be noted or tolerated. An accurate assessment of the acceptability of the vibration and the formulation of vibration limits can only be made with the knowledge of these factors.

For some environments it is possible to evaluate the effects of vibration on human comfort by using the frequency weighted root mean square (r.m.s.) acceleration of a representative period. The weighted r.m.s. acceleration is expressed in meters per second squared [m $s^{-2}$] for translational vibration and radians per second squared [rad $s^{-2}$] for rotational vibration. The weighted r.m.s. acceleration is calculated using:

$$a_w = \left[ \frac{1}{T} \int_0^T a_w^2(t) dt \right]^{0.5}$$

where $a_w(t)$ is the weighted acceleration as a function of time [m $s^{-2}$], and T is the duration of the measurements [s].

Acceptable values of vibration magnitude for comfort in accordance with ISO 2631 [28] depend on many factors which vary with each application. The standard does not define a limit. However, approximate indications of likely reactions to various magnitudes of overall vibration total values are provided (Table 3) [29].

Table 3: Comfort reactions to vibrations

| $a_w$ [m $s^{-2}$] | Perception |
|---|---|
| < 0.315 | Not uncomfortable |
| 0.315 – 0.63 | A little uncomfortable |
| 0.5 - 1 | Fairly uncomfortable |
| 0.8 – 1.6 | Uncomfortable |
| 1.25 – 2.5 | Very uncomfortable |
| > 2 | Extremely uncomfortable |

## 3.3. Conclusion

The analysis showed that the acoustic comfort in a building is determined by the acoustic performance of the rooms in the building (intra- acoustics) and the acoustics between the different rooms in the building (inter-acoustics). The Core Indicator Acoustic Comfort is characterized by four Performance Indicators:

- Background noise
- Reverberation time
- Speech intelligibility
- Structural vibrations

However, it should be noticed that the speech intelligibility is directly connected with, and is often considered to be a function of, the background noise and the reverberation time.
Each Performance Indicator is dependent of the specific indicators or parameters. Table 4 presents the performance indicators and related parameters for acoustic comfort.

Table 4: Performance indicators for acoustic comfort

| Performance Indicator | | Parameter | Description |
|---|---|---|---|
| Background noise (Average noise level over 30 minutes (in a room)) | $L_{Aeq,30min}$ | $R_w$ | The required minimum airborne sound insulation for the separating construction (Weighted sound reduction index) |
| | | $D_{nT(Tmf,max)}$ | Airborne sound insulation between spaces: weighted standardized level difference between two rooms |
| | | $L'_{nT(Tmf,max)}$ | Impact sound transmitted into spaces via the floor |
| Reverberation time | T | $T_{30}$ | Reverberation time, derived from -5 to -35 dB of the decay curve |
| Speech Intelligibility | STI | EDT | Early decay time, derived from 0 to -10 dB of the decay curve |
| | | D | Deutlichkeit (definition), early (0-50 ms) to energy ratio |
| | | C | Clarity, early (0-80 ms) to late (80 ms to ∞) energy ratio |
| | | $T_s$ | Centre time, time of 1. Moment of the energy impulse response |
| | | G | Sound level related to omni-directional free-field radiation at 10m range |
| | | LF | Early lateral (5-80ms) energy ratio, i.e. the energy arriving within the first 80ms from lateral directions ($cos^2$, lateral angle) |
| | | LFC | Early lateral (5-80ms) energy ratio (cos, lateral angle). |
| | NCB/NR | | Noise criterion or noise rating curves |
| Structural vibrations at low frequencies (1-80 Hz) | $a_w$ | $a_w$ | Weighted acceleration |

Analysis and assessment of the parameters presented in Table 4 appears often to be an intensive task in the building design process as well as in a situation when the building has been built. The parameters are dependent of detailed information on the configuration of the building, rooms and spaces in the building. Often, the availability of this information as well as the level of detail is limited. The reader should notice that implementation of the list of performance indicators, as presented in Table 4, is not straightforward. Focusing on the representation of the general acoustic performance of a building by one performance indicator for acoustic comfort, Table 4 has been revised. It is recommended to use the performance indicators presented in Table 5 in an indicator framework for the evaluation of general building performance.

Table 5: Acoustic comfort

| Performance Indicator | | |
|---|---|---|
| Background noise | $L_A$ | [dB] |
| Reverberation time | T | [s] |

# 4. VISUAL COMFORT

Almost all aspects of human behaviour and performance depend heavily on the light one is exposed to. People are very much aware that we need light to see and that the visual system in turn is essential for the proper execution of a wide variety of tasks. Apart from the role of light in visual processes, however, light also turns out to play a major role in a wide variety of non-visual processes as well.

Generally, the function of lighting in a building can be subdivided in three domains: Health and safety, visual performance, and aesthetics [30]. First of all, the lighting of an area should be adequate to ensure that people can live safely, and it should not in itself be a health hazard. Assessment of the visual environment can provide information as whether or not these criteria are met.

Second, the visual performance defines whether the lighting solution in a room is suitable for the performed task(s). Compliance to the standards is critical for the performance of the visual task and thus fulfilling the required activities. For the area, in which a specific task is performed, the lighting fulfils the maintained illuminance, the uniformity of illuminance, the colour rendering, and the absence of glare. The arrangement of the lighting avoids distracting hard shadows, discomforting sources of glare and reflections. The lighting does not flicker, avoids larger dark zones in the room, and meets the conditions of uniformity of illuminance in the area in the surroundings of the visual task. The room should be illuminated evenly with suitable luminance ratios. More specifically, the lighting should avoid glare, should consider a balanced distribution of light which is adjusted to the space, while the walls and the ceiling are pleasantly lit.

Third, aesthetics defines the positive effects of the lighting in a room upon human well-being, both psychologically and biologically. A pleasant environment is conductive to well-being, and will usually result in less stress and better task performance. The lighting contributes to the users' well-being, has activating effects, and adapts to the desired luminance levels. Furthermore, the light looks natural, and stabilizes and supports the natural human biological rhythm. With respect to human well-being and psychological health, the use of daylight and a view to the outside environment is recommended. Health impairments by radiant heat and/or electromagnetic fields are avoided.

As mentioned previously, the function of lighting in a building is categorized in health and safety, visual performance, and aesthetics. Regarding the visual performance, the recommendations and standards for lighting design in workplaces adequately address visual needs and visual comfort. Performance indicators for visual performance and are described by (sub)-indicators and parameters, which are defined in standards and research papers. Regarding human health, well-being and aesthetics, researchers have investigated the non-visual psychological influence of lighting on humans, for example on alertness and mood, establishing causative links between these aspects showed to be difficult [31] [32].

## 4.1. Visual performance

Based on the requirements for optimal visual performance, criteria have been formulated to assure high quality light conditions of the work environment. The European standard NEN-EN 1264-1 (2003) [11], presents the requirements for lighting in the task areas of a building concerning intensity level, colour, glare, luminance ratios, and daylight entrance. In addition, results from previous studies have been evaluated within the framework of the present project.

### 4.1.1. Illuminance

The main requirement for a satisfactory visual performance is a sufficient illuminance for the specific visual task(s) which is/are carried out in the room. The Illuminance of a point on the surface is the amount of light falling on a given surface area, i.e. the luminous flux per unit area. Regarding the lighting quality, which is necessary for performing the visual task in a work situation, illuminance is used as the main indicator.

In a typical office, the European standard [11] requires a maintained illuminance level of 500 lux on the working plane for activities such as writing, reading and typing. In the surroundings of the desk, up to 0.5 meter around it, the lighting level should be at least 300 lux. In the remaining area of the workspace an illuminance level of 200 lux is recommended. Figure 8 presents recommended illuminance levels [11] for rooms with other functions.

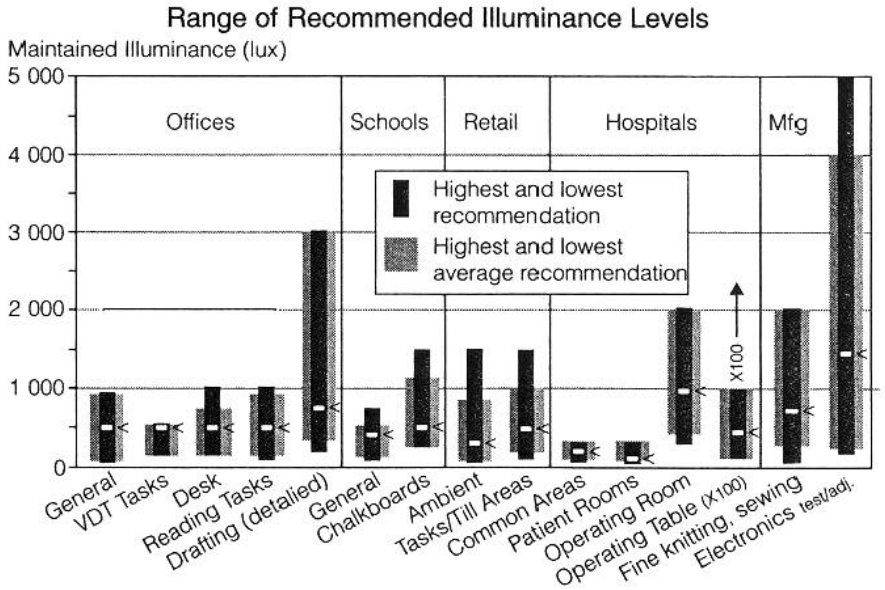



Figure 8: Range of (horizontal) illuminance levels recommended by the European Standard [31]

In addition, while the illuminance of the room is restricted by the ratio between the illuminance in the task area and the surrounding area, the uniformity of the illuminance in the task area and the direct surroundings is restricted by the illuminance presented in Table 6.

Table 6: Uniformity and proportions of the illuminances in a room

| Illuminance of the task area | Illuminance of the direct surroundings |
|---|---|
| ≥750 | 500 |
| 500 | 300 |
| 300 | 200 |
| ≤ 200 | $E_{task}$ |
| Uniformity: ≥ 0.7 | Uniformity: ≥ 0.5 |

### 4.1.2. Luminance

The amount of light falling on a point on the wall is its illuminance, and the amount of reflected light coming back from the wall is its luminance. Illuminance and luminance are closely linked. If all of the light that fell on the wall was reflected, then the values of the illuminance and the luminance would be the same, using appropriate units. If some of the light was absorbed or transmitted, then the values would differ. The reflectance of the wall may be found by comparing the illuminance and the luminance values. The greater the proportion of unwanted reflection from a surface, the more likely a person is to experience annoyance, discomfort and degraded visual performance.

A number of quite distinct lighting-related visual problems, such as discomfort and reduced visual performance, have been grouped together under the heading of 'glare'. These problems have in common the fact that they are all associated with light levels that are relatively high compared to the ambient light levels. Although different forms of glare may occur simultaneously, they are essentially independent because they do not have the same underlying physiological mechanism. It is not surprising, then, that it is possible to have discomfort without disability, and vice versa, even though both will be often found occurring together.

Discomfort glare
Although the mechanism of discomfort glare is unknown, the conditions under which discomfort occurs have been well established for a number of years [30]. Generally, discomfort increases with an increase in the luminance of the glare source, and/or an increase in the angular size of the glare source at the eye. Discomfort decreases with an increase in the luminance of the background, and/or an increase in the angular position of the glare source relative to the line of sight. By definition discomfort is subjective, and discomfort glare is not easily quantified. A given physical configuration of lights will not only give rise to different reported amounts of discomfort from different people, but also to different reported amounts of discomfort from the same person on different occasions. Subjective assessment in this situation is not particularly reliable. On the other hand, the physical parameters of different lighting configurations are, in theory, easy to determine. If it is known how the above four factors (glare source luminance, size, position, and background luminance) interact, it should be possible to measure aspects of the environment and determine on an objective scale how good or how bad the environment is. This is the rationale behind the various glare indices established in different countries—they say little about how an individual will respond, but they do allow an objective evaluation to be made of the lighting configuration.

While the physiological mechanisms involved in discomfort are not understood, the ways in which an extraneous light source can affect visual performance are quite clear [33]. All involve contrast reduction. The degradation of visual performance occurs in one of two ways: a glare source can act directly by reducing the contrast between an object and its background, or indirectly by affecting the eye.

Discomfort glare from both daylight and artificial origin has been the subject of extensive research in the past but, currently, neither a unique reliable prediction model, accepted as standard worldwide, nor does a single monitoring procedure exist [34]. Several different indexes have been proposed as a result of experimental studies relating subjective evaluations to the relevant (measurable) variables affecting the glare phenomenon. Most of these empirical formulas quantify the subjective glare sensation by calculation of a Glare Constant, which is expressed in terms of the measurable physical parameters through equations having the following general structure [35]:

$$G = \frac{L_s^p \omega_s^q}{L_b^r f(\psi)}$$

Where $L_s$ is the glare source luminance, $\omega_s$ is the solid angle subtended by the source at the observation point, $L_b$ is the background luminance excluding the glare source, $f(\psi)$ is a function of the displacement angle j of the source from the observer line of sight, p, q and r are constant weighting exponents.

The Visual Comfort Probability (VCP) method [35], the British Glare Index (BRS or BGI) system [36], the CIE Glare Index (CGI) [37] and the Unified Glare Rating (UGR) system [38] are well known methods. They have all been developed for small artificial lighting sources and are only to a limited extent applicable to large glare sources such as windows [39]. For the evaluation of the magnitude of discomfort glare experienced from windows, the Daylight Glare Index (DGI) is usually applied [34]. Table 7 presents an example of the typical values of the Daylight Glare Index in buildings.

Table 7: Glare indexes

| | DGI |
|---|---|
| Intolerable | > 28 |
| Just intolerable | 28 |
| Uncomfortable | 26 |
| Just uncomfortable | 24 |
| Acceptable | 22 |
| Just acceptable | 20 |
| Perceptible | 18 |
| Just perceptible | ≤ 16 |

However several correlations are available the daylight glare probability (DGP) is generally accepted to give the best prediction of the user's response regarding glare perception [40].

Despite the apparent validity of these studies in carefully-controlled experimental conditions, the evaluation of the glare indices in practice is complicated. While the luminance and size of the glare source(s) are easily measured, there are real difficulties in determining the value of both the background luminance and the glare source position. First, the luminance of different walls and different parts of the ceiling will vary, and the problem arises of what value constitutes the 'true' background luminance. In practice, an 'average' value has to be estimated. Second, there is not one unique glare index for one room position, but rather one glare index for each position in the room and each position of the eyes [30].

Not surprisingly, there is a poor correlation between subjective reports of discomfort and the glare index. Glare prediction models are still being developed, for example [40]. The advantage

of such an index is that it does provide an objective description of the environment. The disadvantage of the index is that this figure does not in itself describe well the subjective discomfort of an individual subjected to that glare.

Disability glare and reflections
Direct disability glare can occur because of a discrete reflection, such as the specular reflection of a light source from the surface of a screen. Here the luminance of both the object (the characters being viewed) and the background (the surrounding screen) are raised by the addition of the extra light but the contrast is reduced. It can also occur because of a diffuse reflecting veil over the whole of the task, as is seen, for example, when a car windscreen mists up. The whole of the scene looks grey and washed out, and both luminance contrast and colour contrast are diminished. These two examples have in common that the contrast between the object and the background is decreased, with a consequent reduction in object visibility. Hence to reduce the disability one should raise the contrast between the task and the background.

The luminance factor is used to characterize the amount of reflectance [30]. The luminance factor is defined as the ratio of the luminance of a reflecting surface, viewed in a given direction, to that of a perfect white diffusing surface identically illuminated. If the reflecting surface is itself a perfect diffuser, then the value of the luminance factor is the same as the reflectance, is independent of the viewing position, and cannot be greater than one.

Indirect disability glare affects the eye and not the visual task. It is seen, for example, when a car approaches at night with its headlights on full beam and your eyes get dazzled.
The disability in this situation has two sources: there is scatter within the eye reducing the retinal image contrast, and the adaptation level of the eye is raised as the car approaches. After the car has passed it takes a little while for the eye to re-adapt to the ambient light level. Like discomfort, the disability is often reduced by raising the light level.

*Uniformity and contrast*
The relative positions of the light source, the visual task, and the observer determine how effectively the task contrast is rendered, and recently a measure of lighting effectiveness, the Contrast Rendering Factor (CRF) has been devised [30]. The CRF has been used mainly in regard to paper-based tasks, which is where it is at its most useful. If the task lighting in an office is suspected to be deficient, then measurement of the CRF would be an appropriate way to investigate the problem. Ideally, the CRF is measured by comparing the contrast of the object under the ambient lighting with its contrast under reference lighting (completely diffuse, unpolarised illumination). The reader should realise that the CRF is specific to a particular target, a particular location, and a particular observer position and is not a measure which describes the lighting alone. So the CRF of writing on matt paper will be different from that of writing on glossy paper under otherwise identical conditions. For additional information regarding the Contrast Rendering Factor, the reader is referred to Boyce (2003) [33].

Generally, the higher the CRF, the more acceptable the visual performance is. This might lead one to suppose that the reference lighting conditions, uniform diffuse illuminance, could be considered as ‘ideal’. However, this is not the case as CRF is not the only criterion by which the directionality of lighting is judged. Uniform, shadow-free lighting gives an extremely bland appearance to an interior, with the solidity of objects being less readily apparent because of the lack of relief.

A further consideration in lighting uniformity is the illuminance distribution over a workplace. The arrangement of the lighting in a room should avoid distracting hard shadows, discomforting glare sources, and distracting reflections. Large differences in illuminance in a room may lead to visual stress and uncomfortable situations. Though the illuminance around the task area may be smaller compared to the illuminance in the task area, the illuminance is restricted by the luminance ratio. The luminance ratio is the luminance of one area divided by the luminance of another area. Luminance ratio limits are recommended to prevent excessive contrast between light and dark. If the contrast between visual fixation points (task: surroundings) is too large, the time required for adaptation of the eye increases and it may slow visual performance and even may cause discomfort and fatigue. The proportion of the luminances is defined as 10:3:1, with respectively (task : direct surroundings : periphery).

### 4.1.3. Flicker

Flicker, noticeable rapid fluctuations in light level, can be a serious problem in artificial environments. Unfortunately, objective measurement of flicker is not simple because it requires rapid-response equipment, normally available only to a lighting specialist. Subjective assessment of flicker is, however, much more feasible and both the area of noticeable flicker and the degree of noticeable flicker can be adequately assessed by descriptive means. Also, because the periphery of the eye is more sensitive than the central area to flicker, subjective assessment may actually be a more relevant method. Hence, when dealing with flicker the precise circumstances under which it is seen, such as the luminance and the position of the source in the visual field, should be noted.

In considering the subjective assessment of flicker, it should be noticed that flicker can have an annoyance or a distractive effect out of all proportion to its physical magnitude. A subjective assessment of the flicker should therefore not only consider the physical aspects of the stimulus, such as the perceived flicker strength, but should also evaluate the psychological effect that the flicker is having on the person. The positive side to flicker is that because it is very attention-getting, its use is a very good visual method of conveying warning information.

Moreover, two further aspects need to be considered. First, some people are especially sensitive to flicker. Epileptics are an extreme example, and for them flicker (particularly at frequencies around 10 Hz) can provoke seizures. Second, flicker which is not visually detectable may still affect parts of the visual system. The human retina responds to flicker at high frequencies (over 100 Hz) even though the light appears steady, and no flicker is seen. It remains to be determined whether other parts of the human visual system are affected by high flicker frequencies, and whether performance or comfort are affected.

### 4.1.4. Colour aspects

With respect to the colour aspects of lighting, the performance can be described by the colour temperature and colour rendering of the lighting.

*Colour rendering*
Different light sources have different colour rendering properties, and the colour of an object is determined both by the spectral composition of the light source, and by the spectral reflectance properties of the object and its surround. When considering the chromatic aspects of the environment, both the colour rendering properties of the light sources and the pleasantness (or otherwise) of the lighting and the environmental colours must be included. The first of these is likely to have been considered by the lighting designer in an environment where it is important, e.g., where colour discrimination or colour matching are included in the tasks performed in that location. The best colour rendering is not always necessary, and other criteria, such as energy consumption, may take precedence. In some situations (such as industrial exteriors and warehouse interiors) the lights may have a simple safety function. Good colour discrimination is not required, for example, if the lighting only has to reveal the presence or absence of objects. Here the cost of running the lights may be a more important criterion than their pleasantness.

In an environment where people have to spend a large proportion of their working time the colour rendering properties of the lighting, or combination of the lighting, plays an increasingly important role. Light sources with poor colour rendering are generally considered to provide a less pleasant environment than those with good rendering.

In addition, the European standard [11] defines a colour rendering index (CRI) for lighting. The colour rendering is a measure of the effect a light source has on the perceived colour of objects and surfaces. Daylight coming from a northern sky is broad-band and is used as a reference illuminant. The lighting in a building is evaluated based on a 100 point scale colour rendering index (CRI) for lamps. Lighting with a relatively high colour rendering index represent virtually all colours natural and vibrant, while low CRI lighting causes some colours to appear washed out. In general, the higher the value of the CRI the better the lamp performs (e.g., incandescent lamps may have a CRI of 99, an artificial daylight fluorescent lamp has a CRI of 93, while a white fluorescent lamp has a CRI of 56). However, these are overall values for the lamps, and a lamp with a high score does not necessarily perform well all over the spectrum, although it should give good rendering of most colours. The European standard advises a colour rendering index (CRI) of at least 80, which means good (50 is bad, 100 is excellent).

*Colour temperature*
The colour temperature (CCT, correlated colour temperature) of an artificial light source is determined by comparing its chromaticity with that of an ideal black-body radiator. The temperature (usually measured in Kelvin (K)) at which the heated black-body radiator matches the colour of the light source is that source's correlated colour temperature.

Chromaticity is an objective specification of the quality of a colour regardless of its luminance. For the description of colour the CIE (Commission Internationale de l'Eclairage) created in 1931 a mathematical model of a colour space. Since the retinal colour receptors in the human eye, cones, are sensitive to short, middle and long wavelength of light, the colour space model is

characterized by three parameters (X,Y,Z), which are related to these three basic colours. Using these parameters it is possible to create an additive colour space based on three colours. The CIE separated the three dimensions of colour into one luminance dimension and a pair of chromaticity dimensions, respectively x and y (Figure 9).

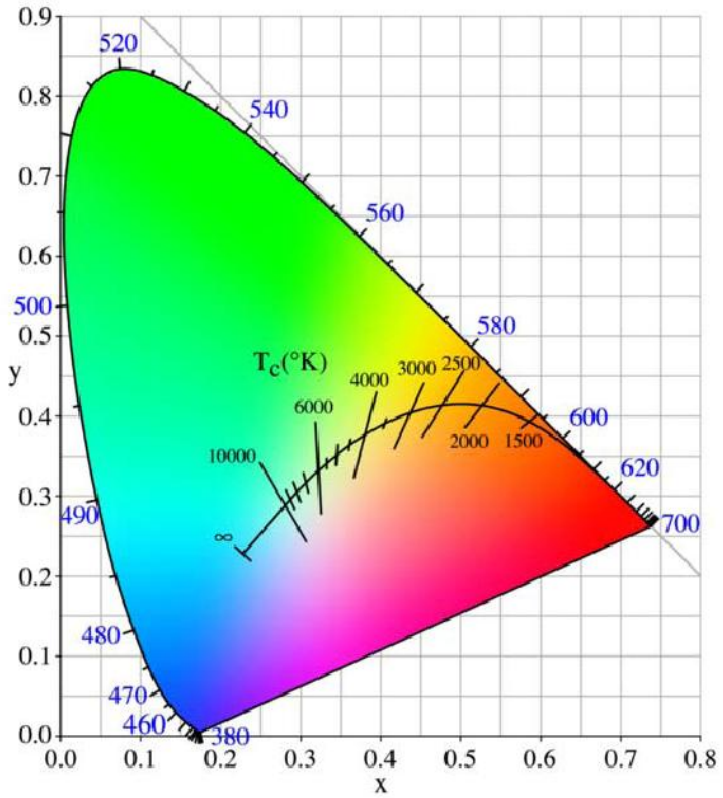



Figure 9: The CIE (1931) chromaticity space with the chromaticities of black-body light sources for various temperatures.

In Figure 9, the CIE (1931) diagram of the x, y chromaticity space including chromaticity of black-body light sources of different temperature, and lines of constant correlated colour temperature is presented. The outer curved boundary is the spectral locus of monochromatic spectra. Concerning the quality of colour properties of lighting, no colour temperature recommendation is given by the European standard [11]. The choice of the lighting colour is psychological and esthetical, and is dependent of other aspects as well, such as the illuminance in a room, the furniture, indoor and outdoor environment. The human perception of the correlated colour temperature is presented in Table 8. Moreover, The CIE (Commission Internationale de l'Eclairage) recommends a colour temperature (CCT) for interior lighting in the range of 3000-6500K.

Table 8: Lighting colour

| Lighting colour | Correlated colour temperature (CCT) [K] |
|---|---|
| Warm | < 3300 K |
| Intermediate | 3300 – 5300 K |
| Cool | > 5300 |

## 4.2. Daylight

The need for windows in buildings, providing natural light, has come into question because of their cost in terms of heat-loss and energy conservation [30]. The scientific evidence for a physiological need for windows is, at best, unproven, however the psychological evidence is clear. A small, windowless room can easily be considered cell-like and restricting, while the presence of a window provides visual access to the outside world. Larger rooms are considered less restrictive, and in a well-controlled environment the absence of windows becomes less important. However, in these windowless environments the information, such as the time of day, and the variety provided by the changing outside light is still absent.

*Human health and well-being*
Light influences the daily rhythm and well-being of humans in a physiological, psychological and biological way. Light not only enables humans to see. Beside visual photoreceptors, the human eye also contains non-visual photoreceptors. Supported by light perception, the human biological clock system tells the human body when to regulate multiple body functions such as body temperature, sleep patterns, cognitive performance, mood, well-being and the release and production of hormones.

Current recommendations for office lighting are purely based on visual criteria. The illuminance on the working plane is the dominant lighting design parameter in offices. This parameter is less relevant for non-visual stimulation. Current offices may not provide sufficient lighting for adequate non-visual stimulation. Furthermore, lighting concepts for office rooms that meet both the human visual and non-visual demands are not available.

Currently, research is carried out to investigate which 'stimulation specifications' healthy lighting concepts have to satisfy. Examples of specifications are intensity, timing, dynamics, direction and spectral composition of (ocular) light exposure. Exact values are not yet known but literature shows that a high lighting level is the prime requirement for a healthy work environment. Daylight, including high intensities and natural dynamics, is an important light source for healthy lighting. The non-visual and psychological aspect of daylight for human health and well-being is important to take into account when assessing the visual comfort in a building.

*Daylight factor*
Daylight can provide temporal variation over the day, as well as spatial and spectral variation within a room. The illumination variation may be quantified as a change in the daylight factor across a room over time. The daylight factor is the ratio of the illuminance from the skylight measured on a horizontal surface within the room to the illuminance from the skylight (not direct sunlight) measured on a horizontal plane which has an unobstructed access to the hemisphere of the sky. At different positions within the room the daylight factor will vary, and if required this variation may be assessed over a room. For interiors where the daylight factor variation is not large, such as rooms with skylights, or rooms that are not too deep, and when the average daylight factor is 5% or greater, an interior will appear generally to be well day-lit. Also, if the illuminance from the sky is not known, the relative daylight factor at different positions within the room will give information about the spread of daylight within the environment.

The pleasantness of variation in spectral content and luminance level is not restricted to natural lighting. On the contrary, in some parts of the world the design of mood lighting provides a considerable source of revenue for interior designers and fixture designers alike.

## 4.3. Conclusion

The analysis showed that the visual comfort in a building is determined by the health and safety, visual performance, and aesthetics. The Core Indicator Visual Comfort is characterized by seven Performance Indicators:

- Illuminance
- Discomfort glare
- Disability glare and reflections
- Uniformity and contrast
- Flicker
- Colour aspects: colour rendering, colour temperature
- Daylight

Each Performance Indicator is dependent of the specific indicators or parameters. Table 9 presents the performance indicators and related indicators/parameters for acoustic comfort.

Table 9: Performance indicators for visual comfort

| Performance Indicator | Indicator/Parameter | Description |
|---|---|---|
| Illuminance | Illuminance | Amount of light falling (luminous flux) on a surface area (task area) |
| Discomfort glare | Daylight Glare Probability | User's discomfort due to glare |
| Disability glare and reflections | Luminance factor | Amount of reflectance |
| Uniformity and Contrast | Contrast Rendering Factor | Effectiveness of contrast rendering |
| | Luminance ratio | Contrast between task and surroundings |
| Flicker | | Noticeable rapid fluctuations in light level |
| Colour Aspects | Correlated Colour Temperature | |
| | Colour Rendering | The effect of a light source on the perceived colour of objects and surfaces |
| Daylight | Daylight factor | The ratio of outside illuminance over inside illuminance |

# 5. INDOOR AIR QUALITY

The quality of indoor air is affected by all components of the environment. The constituents of microclimate are dependent on the temperature and relative humidity of the air, concentration of odours and toxic materials, number of aerosols and microbes in the air, contamination by radioactive gases, static electricity, number of negative and positive ions in the air, etc. Various chemicals are emitted into the air from both natural and man-made (anthropogenic) sources. The quantities may range from hundreds to millions of tonnes annually. Natural air pollution stems from various biotic and abiotic sources such as plants, radiological decomposition, forest fires, volcanoes and other geothermal sources, and emissions from land and water. These result in a natural background concentration that varies according to local sources or specific weather conditions.

The task of reducing levels of exposure to indoor air pollutants is a complex one. It begins with an analysis to determine which chemicals are present in the air, at what levels, and whether likely levels of exposure are hazardous to human health and the environment. It must then be decided whether an unacceptable risk is present. When a problem is identified, mitigation strategies should be developed and implemented so as to prevent excessive risk to public health in the most efficient and cost effective way.

The most direct and important source of air pollution affecting the health of many people is tobacco smoke. Even those who do not smoke may inhale the smoke produced by others (passive smoking). Indoor pollution in general and occupational exposure in particular also contributes substantially to overall human exposure: indoor concentrations of nitrogen dioxide, carbon monoxide, respirable particles, formaldehyde and radon are often higher than outdoor concentrations.

Air pollutants can cause a range of significant effects that require attention: irritation, odour annoyance, and acute and long-term toxic effects. Numerical air quality guidelines either indicate levels combined with exposure times at which no adverse effect is expected in terms of non-carcinogenic endpoints, or they provide an estimate of lifetime cancer risk arising from those substances that are proven human carcinogens or carcinogens with at least limited evidence of human carcinogenicity. It should be noted that the risk estimates for carcinogens do not indicate a safe level, but they are presented so that the carcinogenic potencies of different carcinogens can be compared and an assessment of overall risk made.

It is believed that inhalation of an air pollutant in concentrations and for exposure times below a guideline value will not have adverse effects on health and, in the case of odorous compounds, will not create a nuisance of indirect health significance. This is in line with the definition of health: a state of complete physical, mental and social wellbeing and not merely the absence of disease or infirmity. Nevertheless, compliance with recommendations regarding guideline values does not guarantee the absolute exclusion of effects at levels below such values. For example, highly sensitive groups such as those impaired by concurrent disease or other physiological limitations may be affected at or near concentrations referred to in the guideline values. Health effects at or below guideline values may also result from combined exposure to various chemicals or from exposure to the same chemical by multiple routes.

## 5.1. Indoor air Contaminants

To assess all of these substances would be a multi-volume work, which is not within the scope of this project. Information on contaminants which are relatively common or pose a significant health threat if found in the indoor air are presented in this work. These criteria assume that the adverse health effects from exposure to the chosen contaminants are known. Moreover, there are substances for which the adverse health effects are relatively unknown and are not addressed in this document. The most recent guidelines for indoor air quality in Europe [41] have been published by the World Health Organization in 2000. Furthermore, intensive studies, such as [42], have been performed focusing on performance indicators for indoor air quality. In this report, five classes of indoor air pollutants are categorized: organic pollutants, inorganic pollutants, classical pollutants, indoor air pollutants, and bioaerosols. The following sections present a summary of the pollutants, including an exposure evaluation, a health risk evaluation, and guidelines.

### 5.1.1. Organic pollutants

This section presents an evaluation of the organic pollutants which may be present in the indoor air in a building.

*Acrylonitrile*

On the basis of large-scale calculations using dispersion models, the average annual ambient air concentration of acrylonitrile in the Netherlands was estimated to be about 0.01 $\mu g/m^3$ (1), which is below the present detection limit of 0.3 $\mu g/m^3$. Acrylonitrile concentrations in the air at the workplace have exceeded 100 $mg/m_3$, but shift averages are usually in the range of 1–10 $mg/m^3$.

Because acrylonitrile is carcinogenic in animals and there is limited evidence of its carcinogenicity in humans, it is treated as if it were a human carcinogen. No safe level can therefore be recommended. At an air concentration of 1 $\mu g/m^3$, the lifetime risk, defined as the risk of developing a disease during one's lifetime or dying of the disease, is estimated to be $2 \times 10^{-5}$.

*Benzene*

Sources of benzene in ambient air include cigarette smoke, combustion and evaporation of benzene-containing petrol (up to 5% benzene), petrochemical industries, and combustion processes. Mean ambient air concentrations of benzene in rural and urban areas are about 1 $\mu g/m^3$ and 5–20 $\mu g/m^3$, respectively. Indoor and outdoor air levels are higher near such sources of benzene emission as filling stations.

The most significant adverse effects from prolonged exposure to benzene are haematotoxicity, genotoxicity and carcinogenicity. Benzene is carcinogenic to humans and no safe level of exposure can be recommended.

*Butadiene*

Several different risk assessments have been conducted for butadiene, and a number of these for occupational exposures to butadiene have been summarized by the US Occupational Safety and Health Administration. The study showed that quantitative cancer risk estimates vary widely, in particular depending on the test species used. No definitive conclusions can yet be made as to which species should be used for risk estimates. New, as yet unpublished epidemiological data might have an impact on the risk estimates and hence on the derivation of a guideline value. In the light of these considerations, no guideline value can be recommended at this time.

*Carbon disulfide*

Inhalation represents the main route of entry of carbon disulfide into the human organism. Values in the vicinity of viscose rayon plants range from 0.01 mg/$m^3$ to about 1.5 mg/$m^3$, depending mostly on the distance from the source.

The lowest concentration of carbon disulfide at which an adverse effect was observed in occupational exposure was about 10 mg/m3, which may be equivalent to a concentration in the general environment of 1 mg/m3. In selecting the size of the protection (safety) factor, the expected variability in the susceptibility of the general population was taken into account, and a protection factor of 10 was considered appropriate. This leads to the recommendation of a guideline value of 100 μg/$m^3$, with an averaging time of 24 hours. It is believed that below this value adverse health effects of environmental exposure to carbon disulfide (outdoor or indoor) are not likely to occur.

*Carbon dioxide*

Carbon dioxide is a normal body constituent, which is generated by respiration. It is a natural component of air and background levels range from 350-500 ppm and is rising each year due to releases from sequestered forms. The main source of carbon dioxide in the indoor environment is the occupants. Other indoor sources include carbon-based fuel combustion, and aerobic decomposition processes.

Carbon dioxide is essential to normal health but is an asphyxiant, a respiratory stimulant and a depressant of the central nervous system. At low doses (< 1000 ppm), carbon dioxide is used as an indicator of inadequate fresh air ventilation (American Society of Heating Refrigerating and Air-Conditioning Engineers, 1997). Acute exposure levels of 40000 ppm (100 times normally encountered concentrations) increase human respiratory rates to double normal levels. Increases in heart rate and blood pressure are noted at exposure levels of 75000 ppm. Other reported symptoms at this exposure level include dyspnoea, dizziness, and headache. Exposure levels of 100,000 ppm produced eye flickering, twitching, headache, dizziness, dyspnoea, sweating, restlessness, and a sensation of fullness in the head. Exposure levels over 100000 ppm a loss of consciousness occurs. Exposure levels over 170000 ppm are considered life threatening [42].

There are two motivations for carbon dioxide standards: toxicity concerns, and occupant comfort levels and ventilation requirements. The industrial workplace standards are concerned with toxic concentrations of carbon dioxide. Indoor air quality standards are concerned with the comfort of the occupants. With respect to the toxicity of carbon dioxide, the World Health Organization recommends a guideline of 6600 ppm for short term exposure. Moreover,

ASHRAE suggests that indoor carbon dioxide levels should be restricted to approximately 650-1000 ppm above ambient levels [43].

*Carbon monoxide*

Global background concentrations of carbon monoxide range between 0.06 mg/m$^3$ and 0.14 mg/m$^3$ (0.05–0.12 ppm). In urban traffic environments of large European cities, the 8-hour average carbon monoxide concentrations are generally lower than 20 mg/m$^3$ (17 ppm) with short-lasting peaks below 60 mg/m$^3$ (53 ppm).

When carbon monoxide is inhaled, approximately 80-90% of the absorbed carbon monoxide binds with haemoglobin to form carboxyhaemoglobin (COHb), which is a specific biomarker of exposure in blood. The binding of carbon monoxide with haemoglobin to form COHb reduces the oxygen-carrying capacity of the blood and impairs the release of oxygen from haemoglobin to extravascular tissues. These are the main causes of tissue hypoxia produced by carbon monoxide at low exposure levels. At higher concentrations the rest of the absorbed carbon monoxide binds with other haem proteins. The toxic effects of carbon monoxide become evident in organs and tissues with high oxygen consumption such as the brain, the heart, exercising skeletal muscle and the developing foetus.

The following guidelines, which take into account all the known physiological variables affecting carbon monoxide uptake, have been established:

- 100 mg/m$^3$ (90 ppm) for 15 minutes
- 60 mg/m$^3$ (50 ppm) for 30 minutes
- 30 mg/m$^3$ (25 ppm) for 1 hour
- 10 mg/m$^3$ (10 ppm) for 8 hours

*1,2-Dichloroethane*

Rural or background atmospheric concentrations in western Europe and North America are approximately 0.2 μg/m$^3$, and the limited data available on indoor concentrations show that they are about the same. Average levels in cities vary between 0.4 μg/m$^3$ and 1.0 μg/m$^3$, increasing to 6.1 μg/m$^3$ near petrol stations, parking garages and production facilities.

Human studies point to effects on the central nervous system and the liver. Moreover, regarding mutagenicity as an endpoint and to the causal connections between DNA damage and the initiation of carcinogenicity, 1,2-dichloroethane has been shown to be weakly mutagenic. The value of 0.7 mg/m$^3$ for continuous exposure (averaging time 24 hours) is recommended as a guideline value. Since this value is above current environmental levels and present exposures are not of concern to health, this guideline relates only to accidental release episodes or specific indoor pollution problems [41].

*Dichloromethane*

Mean outdoor concentrations of dichloromethane are generally below 5 μg/m$^3$ [44]. Significantly higher concentrations (by at least one order of magnitude) may occur close to industrial emission sources. Indoor air concentrations are variable but tend to be about three times greater than outdoor values. Under certain circumstances, much higher values (up to 4000 μg/m$^3$) may be recorded indoors, particularly with use of paint stripping solutions [45].

Exposures of the general population occur principally through the use of dichloromethane-containing consumer products.

The critical effects of dichloromethane include effects on the central nervous system, the production of carboxyhaemoglobin (COHb) and carcinogenicity. The impairment of behavioural or sensory responses may occur in humans following acute inhalation exposure at levels exceeding 1050 mg/m3 (300 ppm) for short durations, and the effects are transient.

The health risks of exposure to dichloromethane have been considered in detail by an International Programme on Chemical Safety (IPCS) expert group. Given the data on interspecies differences in metabolism and comparative cancer risks, that group concluded that carcinogenicity was not the critical endpoint for risk assessment purposes. It is unlikely that ambient air exposures represent a health concern with reference to any cancer endpoint, since concentrations of dichloromethane in ambient air are orders of magnitude lower than levels associated with direct adverse effects on the central nervous system or on COHb production in humans. Consequently, a guideline value of 3 mg/$m^3$ is recommended. In addition, the weekly average concentration should not exceed one seventh (0.45 mg/$m^3$) of this 24-hour guideline, given the half-life of COHb [41].

*Formaldehyde*

The major route of exposure to formaldehyde is inhalation.

Table 10 shows the contribution of the various atmospheric environments to non-occupational air levels. Indoor air concentrations are several orders of magnitude higher than levels in ambient air. Owing to the extremely high concentrations of formaldehyde in tobacco smoke, smoking constitutes a major source of formaldehyde [46].

Predominant symptoms of formaldehyde exposure in humans are irritation of the eyes, nose and throat, together with concentration-dependent discomfort, lachrymation, sneezing, coughing, nausea, dyspnoea and finally death. The lowest concentration that has been associated with nose and throat irritation in humans after short-term exposure is 0.1 mg/m$^3$, although some individuals can sense the presence of formaldehyde at lower concentrations. To prevent significant sensory irritation in the general population, an air quality guideline value of 0.1 mg/m$^3$ as a 30-minute average is recommended. Since this is over one order of magnitude lower than a presumed threshold for cytotoxic damage to the nasal mucosa, this guideline value represents an exposure level at which there is a negligible risk of upper respiratory tract cancer in humans.

Table 10: Average exposure concentrations to formaldehyde [46]

| Source | Concentration (mg/m$^3$) | Exposure (mg/day) |
|---|---|---|
| Ambient air (10% of time; 2 m$^3$/day) | 0.001–0.02 | 0.002–0.04 |
| Indoor air | | |
| Home (65% of time; 10 m$^3$/day) | | |
| – conventional | 0.03–0.06 | 0.3–0.6 |
| – mobile home | 0.1 | 1.0 |
| – environmental tobacco smoke | 0.05–0.35 | 0.5–3.5 |
| Workplace (25% of time; 8 m$^3$/day) | | |
| – without occupational exposure | 0.03–0.06 | 0.2–0.5 |
| – with occupational exposure | 1.0 | 8.0 |
| – environmental tobacco smoke | 0.05–0.35 | 0.4–2.8 |
| Smoking (20 cigarettes/day) | 60–130 | 0.9–2.0 |

*Polycyclic aromatic hydrocarbons*

Polycyclic aromatic hydrocarbons (PAHs) are formed during incomplete combustion or pyrolysis of organic material and in connection with the worldwide use of oil, gas, coal and wood in energy production. Additional contributions to ambient air levels arise from tobacco smoking, while the use of unvented heating sources can increase PAH concentrations in indoor air. Because of such widespread sources, PAHs are present almost everywhere. PAHs are complex mixtures of hundreds of chemicals, including derivatives of PAHs, such as nitro-PAHs and oxygenated products, and also heterocyclic PAHs. The biological properties of the majority of these compounds are as yet unknown. Benzo[a]pyrene (BaP) is the PAH most widely studied, and the abundance of information on toxicity and occurrence of PAHs is related to this compound. Current annual mean concentrations of BaP in major European urban areas are in the range 1–10 ng/m$^3$. In rural areas, the concentrations are < 1 ng/m$^3$ [47] [48].

Because several PAHs have been shown to be carcinogenic, and many more have been shown to be genotoxic in in-vitro assays, a suitable indicator for the carcinogenic fraction of the large number of PAHs in ambient air is desirable. The most appropriate indicator for the carcinogenic PAHs in air seems to be BaP concentrations, given present knowledge and the existing database. Assessment of risks to health of a given mixture of PAHs using this indicator approach would entail, first, measurement of the concentration of BaP in a given mixture present in a medium such as air. Then, assuming that the given mixture resembles that from coke ovens, the unit risk estimate is applied in tandem with the measured BaP air concentration to obtain the lifetime cancer risk at this exposure level.

No specific guideline value can be recommended for PAHs as such in air. These compounds are typically constituents of complex mixtures. Some PAHs are also potent carcinogens, which may interact with a number of other compounds. In addition, PAHs in air are attached to particles, which may also play a role in their carcinogenicity. Although food is thought to be the major source of human exposure to PAHs, part of this contamination may arise from air pollution with PAHs. The levels of PAHs in air should therefore be kept as low as possible [41].

*Polychlorinated biphenyls*

Polychlorinated biphenyls PCB levels have been shown to be higher in indoor air than in ambient air. Inhalation exposure to PCBs, assuming an indoor air level of 3 ng/$m^3$ in an uncontaminated building and an inhaled volume of 20 m3 of air per day for adults, is approximately 0.001 μg/kg BW per day. In contaminated buildings concentrations above 300 ng/$m^3$ have been found. In buildings using PCB-containing sealants, levels up to 7500 ng/$m^3$ have been found. In ambient air there is a wide variation in the measurements from non-industrialized (e.g. 0.003 ng/$m^3$) and industrial/urban areas (e.g. 3 ng/$m^3$). The levels of dioxin-like PCBs cannot be estimated owing to the lack of congener specific analytical data.

However, it should be noticed that food is the main source of human intake of PCBs. Therefore, an air quality guideline for PCBs is not proposed because direct inhalation exposures constitute only a small proportion of the total exposure, in the order of 1–2% of the daily intake from food [41].

*Polychlorinated dibenzodioxins and dibenzofurans*

Food is the main source of human intake of polychlorinated dibenzodioxins (PCDDs) and dibenzofurans (PCDFs); intake through drinking-water is negligible. Inhalation exposure to PCDDs and PCDFs is generally low. Assuming an ambient air toxic equivalent level of 0.1 pg/m3 and an inhaled volume of air of 20 m3/day for adults, inhalation intake would amount to about 1% of the dietary intake, but may in certain extreme situations (areas close to point emission sources or contaminated indoor air) approach the dietary intake.

Urban ambient toxic equivalent air concentrations of PCDDs and PCDFs are estimated to be about 0.1 pg/$m^3$. However, large variations have been measured. Although such an air concentration is only a minor contributor to direct human exposure, it is a major contributor to contamination of the food chain. It is difficult, however, to calculate indirect exposure from contamination of food via deposition from ambient air. Air concentrations of 0.3 pg/$m^3$ or higher are indications of local emission sources that need to be identified and controlled.

An air quality guideline for PCDDs and PCDFs is not proposed because direct inhalation exposures constitute only a small proportion of the total exposure, generally less than 5% of the daily intake from food.

*Styrene*

Concentrations of styrene in rural ambient air are generally less than 1 μg/$m^3$, while indoor air in such locations may contain several μg/$m^3$. Levels in polluted urban areas are generally less than 20 μg/$m^3$ but can be much higher in newly built houses containing styrene-based materials.

Potentially critical effects for the derivation of a guideline for styrene are considered to be carcinogenicity/genotoxicity and neurological effects, including effects on development. Styrene in its pure form has an odour detection threshold of 70 μg/$m^3$. Its pungent odour is recognized at concentrations three to four times greater than this threshold value.

Although genotoxic effects in humans have been observed at relatively low concentrations, they were not considered as critical endpoints for development of a guideline, in view of the equivocal evidence for the carcinogenicity of styrene.

In occupationally exposed populations, subtle effects such as reductions in visuomotor accuracy and verbal learning skills [49] [50] and subclinical effects on colour vision have been observed at concentrations as low as 107–213 mg/m$^3$ (25–50 ppm) [51]. Taking the lower number of this range for precautionary reasons, results in a guideline of 0.26 mg/m$^3$ (weekly average). This value should also be protective for the developmental neurological effects observed in animal species. Alternatively, the air quality guideline could also be based on the odour threshold. In that case, the peak concentration of styrene in air should be kept below the odour detection threshold level of 70 μg/m$^3$ as a 30-minute average.

*Tetrachloroethylene*

Ambient air concentrations of tetrachloroethylene are generally less than 5 μg/m$^3$ in urban areas and typically less than 1 μg/m$^3$ in rural areas. Indoor concentrations are generally less than 5 μg/m$^3$. Indoor tetrachloroethylene air levels may rise to more than 1 mg/m$^3$ in close proximity to dry-cleaning operations where tetrachloroethylene is used as a cleaning solvent or in homes where dry-cleaned clothing is often worn. Inhalation of tetrachloroethylene is the major route of exposure in the general population [52].

The main health effects of concern are cancer and effects on the central nervous system, liver and kidneys. On the basis of the overall health risk evaluation, a guideline of 0.25 mg/m$^3$ is currently established. However, the concern about a possible carcinogenic effect of tetrachloroethylene exposure in humans should be addressed through in-depth risk evaluation in the near future [41].

*Toluene*

Mean ambient air concentrations of toluene in rural areas are generally less than 5 μg/m$^3$, while urban air concentrations are in the range 5–150 μg/m$^3$. Concentrations may be higher close to industrial emission sources.

Toluene in its pure form has an odour detection threshold of 1 mg/m$^3$. Its odour is recognized at concentrations about ten times greater than this threshold value [53]. The acute and chronic effects of toluene on the central nervous system are the effects of most concern. Toluene may also cause developmental decrements and congenital anomalies in humans, and these effects are supported by findings of studies on animals, for example foetal development retardation, skeletal anomalies, low birth weight and developmental neurotoxicity. The potential effects of toluene on reproduction and hormone balance in women, coupled with findings of hormone imbalances in exposed males, are also of concern. Limited information suggests an association between occupational toluene exposure and spontaneous abortions. Both the human and animal data indicate that toluene is ototoxic at elevated exposures. Sensory effects have also been found. Toluene has minimal effects on the liver and kidney, except in cases of toluene abuse. There has been no indication that toluene is carcinogenic in bioassays conducted to date, and the weight of available evidence indicates that it is not genotoxic.

The lowest-observed-adverse-effect level for effects on the central nervous system from occupational studies is approximately 332 mg/m$^3$ (88 ppm). A guideline value of 0.26 mg/m$^3$ is established from these data. This guideline value should be applied as a weekly average. Alternatively, the air quality guideline could also be based on the odour threshold. In this case, the peak concentrations of toluene in air should be kept below the odour detection threshold level of 1 mg/m$^3$ as a 30-minute average [41].

*Trichloroethylene*

The average ambient air concentrations of trichloroethylene are less than 1 μg/m$^3$ in rural areas and up to 10 μg/m$^3$ in urban areas. Concentrations in indoor air are typically similar, although higher concentrations can be expected in certain areas, such as in proximity to industrial operations. Inhalation of airborne trichloroethylene is the major route of exposure for the general population.

The main health effects of concern with trichloroethylene are cancer, and effects on the liver and the central nervous system [54]. Positive associations between exposure to trichloroethylene and risks for cancer of the liver and biliary tract and non-Hodgkin lymphomas were observed in epidemiological studies on cancer in humans. Because the available evidence indicates that trichloroethylene is genotoxic and carcinogenic, no safe level can be recommended [41].

*Vinyl chloride*

Calculations based on dispersion models indicate that 24-hour average concentrations of 0.1–0.5 μg/m$^3$ exist as background levels in much of Western Europe, but such concentrations are below the current detection limit (approximately 1.0 μg/m$^3$). In the vicinity of vinyl chloride (VC) and polyvinyl chloride (PVC) production facilities 24-hour concentrations can exceed 100 μg/m$^3$, but are generally less than 10 μg/m$^3$ at distances greater than 1 km from plants. The half-time of VC in the air is calculated to be 20 hours; this figure is based on measured rates of reaction with hydroxyl radicals and their concentrations in the air [55].

Vinyl chloride is a human carcinogen and the critical concern with regard to environmental exposures to VC is the risk of malignancy. No safe level can be indicated [41].

### 5.1.2. Inorganic pollutants

*Arsenic*

There are many arsenic compounds, both organic and inorganic, in the environment. Airborne concentrations of arsenic range from 1 ng/$m^3$ to 10 ng/$m^3$ in rural areas and from a few nanograms per cubic metre to about 30 ng/$m^3$ in noncontaminated urban areas. Near emission sources, such as nonferrous metal smelters and power plants burning arsenic-rich coal, concentrations of airborne arsenic can exceed 1 μg/$m^3$.

Arsenic is a human carcinogen. Inorganic arsenic can have acute, subacute and chronic effects, which may be either local or systemic. Lung cancer is considered to be the critical effect following inhalation. An increased incidence of lung cancer has been seen in several occupational groups exposed to inorganic arsenic compounds. Some studies also show that populations near emission sources of inorganic arsenic, such as smelters, have a moderately elevated risk of lung cancer [56].

Present risk estimates have been derived from studies in exposed human populations in Sweden and the United States. A safe level for inhalation exposure cannot be recommended [41].

*Asbestos*

Actual indoor and outdoor concentrations in air range from below one hundred to several thousand fibres per $m^3$.

On the basis of the evidence from both experimental and epidemiological studies, it is clear that asbestos inhalation can cause asbestosis, lung cancer and mesothelioma. The evidence that ingested asbestos causes gastrointestinal or other cancers is insufficient. Furthermore, the carcinogenic properties of asbestos are most probably due to its fibre geometry and remarkable integrity; other fibres with the same characteristics may also be carcinogenic. Current environmental concentrations of asbestos are not considered a hazard with respect to asbestosis. However, a risk of mesothelioma and lung cancer from the current concentrations cannot be excluded.

Asbestos is a proven human carcinogen. No safe level can be proposed for asbestos because a threshold is not known to exist. Exposure should therefore be kept as low as possible [41].

*Cadmium*

It is not possible to carry out a dose-response analysis for cadmium in air solely on the basis of epidemiological data collected in the general population, since the latter is exposed to cadmium mainly via food or tobacco smoking. In addition, the recently reported renal effects in areas of Belgium and the Netherlands polluted by cadmium refer to historical contamination of the environment. Assuming, however, that the only route of exposure is by inhalation, an indirect estimate of the risk of renal dysfunction or lung cancer can be made on the basis of data collected in industrial workers.

The International Agency for Research on Cancer (IARC) has classified cadmium and cadmium compounds as human carcinogens, having concluded that there was sufficient evidence that cadmium can produce lung cancers in humans and animals exposed by inhalation [57]. Because of the identified and controversial influence of concomitant exposure to arsenic in the epidemiological study, however, no reliable unit risk can be derived to estimate the excess lifetime risk for lung cancer.

The finding of renal effects in areas contaminated by past emissions of cadmium indicates that the cadmium body burden of the general population in some parts of Europe cannot be further increased without endangering renal function. To prevent any further increase of cadmium in agricultural soils likely to increase the dietary intake of future generations, a guideline of 5 ng/$m^3$ is established.

*Chromium*

Chromium is ubiquitous in nature. Available data, generally expressed as total chromium, show a concentration range of 5–200 ng/$m^3$. There are few valid data on the valence and bioavailability of chromium in the ambient air possible [41].

Chromium(III) is recognized as a trace element that is essential to both humans and animals. Chromium(VI) compounds are toxic and carcinogenic, but the various compounds have a wide range of potencies. As the bronchial tree is the major target organ for the carcinogenic effects of chromium(VI) compounds and cancer primarily occurs following inhalation exposure, uptake in the respiratory organs is of great significance with respect to the cancer hazard and the subsequent risk of cancer in humans. IARC has stated that for chromium and certain chromium compounds there is sufficient evidence of carcinogenicity in humans [58].

Information on the speciation of chromium in ambient air is essential since, when inhaled, only hexavalent chromium is carcinogenic in humans. The available data are derived from studies among chromium(VI)-exposed workers. Moreover, no safe level of chromium(VI) can be recommended.

*Fluoride*

Exposure of the general European population to fluoride in its various chemical forms is highly variable. In heavily industrialized urban areas, typical daily inhalation intakes are in the range 10–40 μg/day (0.5–2 μg/$m^3$), and in some cases are as high as 60 μg/day (3 μg/$m^3$). Fluorides are emitted to the atmosphere in both gaseous and particulate forms, but studies typically only report total fluoride content. The main sources of fluoride intake by humans are food and water. Except for occupational exposure, exposure to fluoride by inhalation is negligible. Regarding occupational exposure, the daily amount of fluoride inhaled, assuming a total respiratory rate of 10 $m^3$ during a working day, could be 10–25 mg when the air concentration is at the most frequent exposure limits of 1–2.5 mg/m3.

The most important long-term adverse effect of fluorides on human populations is endemic skeletal fluorosis. The 1-hour reference exposure level to protect against any respiratory irritation is about 0.6 mg/$m^3$, and the level to protect against severe irritation from a once-in-a-lifetime release is about 1.6 mg/$m^3$ [59].

Skeletal fluorosis is associated with a systemic uptake exceeding 5 mg/day in a relatively sensitive section of the general population. Systemic uptake from food and fluoridated water is about 3 mg/day. It is highly unlikely that ambient air concentrations of fluorides could pose any material risk of fluorosis.

It has been recognized that fluoride levels in ambient air should be less than 1 $\mu g/m^3$ to prevent effects on livestock and plants. These concentrations will also sufficiently protect human health.

*Hydrogen sulfide*

Typical symptoms and signs of hydrogen sulfide intoxication are most often caused by relatively high concentrations in occupational exposures. Low-level concentrations can occur more or less continuously in certain industries, such as in viscose rayon and pulp production, at oil refineries and in geothermal energy installations. In geothermal areas there is a risk of exposure to hydrogen sulfide for the general population. The biodegradation of industrial wastes has been reported to cause ill effects in the general population. An accidental release of hydrogen sulfide into the air surrounding industrial facilities can cause very severe effects, as at Poza Rica, Mexico, where 320 people were hospitalized and 22 died. The occurrence of low-level concentrations of hydrogen sulfide around certain industrial installations is a well known fact.

The first noticeable effect of hydrogen sulfide at low concentrations is its unpleasant odour. Conjunctival irritation is the next subjective symptom and can cause so-called gas eye at hydrogen sulfide concentrations of 70– 140 $mg/m^3$. Other effects of higher hydrogen sulfide concentrations are strong central nervous system stimulation, hyperpnoea followed by respiratory arrest, and immediate collapse with paralysis of respiration.

The Lowest-observed-adverse-effect level of hydrogen sulfide is 15 $mg/m^3$, when eye irritation is caused. In order to avoid substantial complaints about odour annoyance among the exposed population, hydrogen sulfide concentrations should not be allowed to exceed 7 $\mu g/m^3$, with a 30-minute averaging period.

*Lead*

Average air lead levels are usually below 0.15 $\mu g/m^3$ at nonurban sites. Urban air lead levels are typically between 0.15 and 0.5 $\mu g/m^3$ in most European cities [60]. Additional routes of exposure must not be neglected, such as lead in dust, a cause of special concern for children.

Guidelines for lead in air will be based on the concentration of lead in blood. Critical effects to be considered in the adult organism include elevation of free erythrocyte protoporphyrin, whereas for children cognitive deficit, hearing impairment and disturbed vitamin D metabolism [61] are taken as the decisive effects. All of these effects are considered adverse. A critical level of lead in blood of 100 $\mu g/l$ is proposed [41]. Since both direct and indirect exposure of young children to lead in air occurs, the air guidelines for lead should be accompanied by other preventive measures. These should specifically take the form of monitoring the lead content of dust and soils arising from lead fallout. The normal hand-to-mouth behaviour of children with regard to dust and soil defines these media as potentially serious sources of exposure. A specific monitoring value is not recommended [41].

*Manganese*

In urban and rural areas without significant manganese pollution, annual averages are mainly in the range of 0.01–0.07 μg/m$^3$; near foundries the level can rise to an annual average of 0.2–0.3 μg/m$^3$ and, where ferro- and silico-manganese industries are present, to more than 0.5 μg/m$^3$, with individual 24-hour concentrations sometimes exceeding 10 μg/m$^3$ [62] [63].

The toxicity of manganese varies according to the route of exposure. By ingestion, manganese has relatively low toxicity at typical exposure levels and is considered a nutritionally essential trace element. By inhalation, however, manganese has been known since the early nineteenth century to be toxic to workers. Manganism is characterized by various psychiatric and movement disorders, with some general resemblance to Parkinson's disease in terms of difficulties in the fine control of some movements, lack of facial expression, and involvement of underlying neuroanatomical (extrapyramidal) and neurochemical (dopaminergic) systems [64]. Respiratory effects such as pneumonitis and pneumonia and reproductive dysfunction such as reduced libido are also frequently reported features of occupational manganese intoxication. The available evidence is inadequate to determine whether or not manganese is carcinogenic; some reports suggest that it may even be protective against cancer. Based on this mixed but insufficient evidence, the US Environmental Protection Agency has concluded that manganese is not classifiable as to human carcinogenicity [65]. The International Agency for Research on Cancer (IARC) has not evaluated manganese.

A guideline value for manganese of 0.15 μg/m$^3$ was derived by World Health Organization [41]. The guideline value should be applied as an annual average.

*Mercury*

In areas remote from industry, atmospheric levels of mercury are about 2–4 ng/m$^3$, and in urban areas about 10 ng/m$^3$. This means that the daily amount absorbed into the bloodstream from the atmosphere as a result of respiratory exposure is about 32–64 ng in remote areas, and about 160 ng in urban areas. However, this exposure to mercury from outdoor air is marginal compared to exposure from dental amalgams, given that the estimated average daily absorption of mercury vapour from dental fillings varies between 3000 and 17 000 ng.

It is necessary to take into account the different forms of mercury in the atmosphere, such as mercury vapour, inorganic compounds and methylmercury compounds, and the intake of these forms of mercury from other media. The atmosphere and dental amalgam are the sole sources of exposure to mercury vapour, whereas the diet is the dominant source of methylmercury compounds.

Current levels of mercury in outdoor air, except for regional hot spots, are typically in the order of 0.005–0.010 μg/m$^3$ and thus are marginal compared to exposure from dental amalgam. The exposure to mercury from outdoor air at these air levels is not expected to have direct effects on human health.

The predominant species of mercury present in air, $Hg^0$, is neither mutagenic nor carcinogenic. Exposure to airborne methylmercury is 2-3 orders of magnitude below the food-related daily intake and will, in this context, be regarded as insignificant. It is thus only possible to derive a numerical guideline for inhalation of inorganic mercury, by including mercury vapour and divalent mercury.

Based on the lowest-observed-adverse-effect levels for mercury vapour are around 15–30 μg/m$^3$, a guideline for inorganic mercury vapour of 1 μg/m$^3$ as an annual average has been established [41]. Since cationic inorganic mercury is retained only half as much as the vapour, the guideline also protects against mild renal effects caused by cationic inorganic mercury. Present knowledge suggests, however, that effects on the immune system at lower exposures cannot be excluded.

*Nickel*

Nickel is present throughout nature and is released into air and water both from natural sources and as a result of human activity. In non-smokers, about 99% of the estimated daily nickel absorption stems from food and water; for smokers the figure is about 75%. Nickel levels in the ambient air are in the range 1–10 ng/m$^3$ in urban areas, although much higher levels (110–180 ng/m$^3$) have been recorded in heavily industrialized areas and larger cities. There is, however, limited information on the species of nickel in ambient air.

Allergic skin reactions are the most common health effect of nickel, affecting about 2% of the male and 11% of the female population. Nickel content in consumer products and possibly in food and water are critical for the dermatological effect. The respiratory tract is also a target organ for allergic manifestations of occupational nickel exposure. Nickel has a strong and prevalent allergenic potency. There is no evidence that airborne nickel causes allergic reactions in the general population, although this reaction is well documented in the working environment.

Even if the dermatological effects of nickel are the most common, such effects are not considered to be critically linked to ambient air levels.

*Platinum*

The information on levels of exposure to soluble platinum compounds in the general environment, and there are no authenticated observations on adverse health effects in the population resulting from such exposure, is limited. Ambient air concentrations of total platinum in various urban exposure situations, assuming an average emission rate of approximately 20 ng/km from the monolithic three-way catalyst, were estimated by the US Environmental Protection Agency [66].

In occupational settings, sensitization reactions have been observed for soluble platinum down to the limit of detection of 0.05 μg/m$^3$. However, these effects have occurred only in individuals previously sensitized by higher exposure levels. It is unlikely that the general population exposed to ambient concentrations of soluble platinum, which are at least three orders of magnitude lower, will develop similar effects. At present no specific guideline value is recommended but further studies are required, in particular on the speciation of platinum in the environment [41]

*Vanadium*

The natural background level of vanadium in air in Canada has been reported to be in the range 0.02–1.9 ng/m$^3$ [67]. Vanadium concentrations recorded in rural areas varied from a few

nanograms to tenths of a nanogram per $m^3$, and in urban areas from 50 ng/$m^3$ to 200 ng/$m^3$. In cities during the winter, when fuel oil with a high vanadium content was used for heating, concentrations as high as 2000 ng/$m^3$ were reported. Air pollution by industrial plants may be less than that caused by power stations and heating equipment. The concentrations of vanadium in workplace air (0.01–60 mg/$m^3$) are much higher than those in the general environment.

The acute and chronic effects of vanadium exposure on the respiratory system of occupationally exposed workers should be regarded as the most significant factors when establishing air quality guidelines. Most of the clinical symptoms reported reflect irritative effects of vanadium on the upper respiratory tract, except at higher concentrations (above 1 mg vanadium per m3), when more serious effects on the lower respiratory tract are observed. Chronic exposure to vanadium compounds revealed a continuum in the respiratory effects, ranging from slight changes in the upper respiratory tract, with irritation, coughing and injection of pharynx, detectable at 20 μg/$m^3$, to more serious effects such as chronic bronchitis and pneumonitis, which occurred at levels above 1 mg/$m^3$.

Available data from occupational studies suggest that the lowest-observed-adverse-effect level of vanadium can be assumed to be 20 μg/$m^3$, based on chronic upper respiratory tract symptoms. It is believed that below 1 μg/$m^3$ (averaging time 24 hours) environmental exposure to vanadium is not likely to have adverse effects on health. The available evidence indicates that the current vanadium levels generally found in industrialized countries are not in the range associated with potentially harmful effects.

### 5.1.3. Classical pollutants

*Nitrogen dioxide*

Levels of nitrogen dioxide vary widely because a continuous baseline level is frequently present, with peaks of higher levels superimposed. Natural background annual mean concentrations are in the range 0.4–9.4 μg/$m^3$. Outdoor urban levels have an annual mean range of 20–90 μg/$m^3$ and hourly maxima in the range 75–1015 μg/$m^3$. Levels indoors where there are unvented gas combustion appliances may average more than 200 μg/$m^3$ over a period of several days. A maximum 1-hour peak may reach 2000 μg/$m^3$. For briefer periods, even higher concentrations have been measured.

Despite the large number of acute controlled exposure studies on humans, several of which used multiple concentrations, there is no evidence for a clearly defined concentration–response relationship for nitrogen dioxide exposure. For acute exposures, only very high concentrations (1990 μg/$m^3$; > 1000 ppb) affect healthy people. Asthmatics and patients with chronic obstructive pulmonary disease are clearly more susceptible to acute changes in lung function, airway responsiveness and respiratory symptoms.

Although there is no particular study or set of studies that clearly support selection of a specific numerical value for an annual average guideline, the database nevertheless indicates a need to protect the public from chronic nitrogen dioxide exposure. For example, indoor air studies with a strong nitrogen dioxide source, such as gas stoves, suggest that an increment of about 30 μg/$m^3$ (2-week average) is associated with a 20% increase in lower respiratory illness in children aged 5–12 years. However, the affected children had a pattern of indoor exposure that included peak exposures higher than those typically encountered outdoors.

On these grounds, it is proposed that a long-term guideline for nitrogen dioxide be established. Selecting a well supported value based on the studies reviewed has not been possible, but it has been noted that a prior review conducted for the Environmental Health Criteria document on nitrogen oxides recommended an annual value of 40 $\mu g/m^3$ [68]. In the absence of support for an alternative value, this figure is recognized as an air quality guideline.

*Ozone and other photochemical oxidants*

Ozone and other photochemical oxidants are formed by the action of short-wavelength radiation from the sun on nitrogen dioxide. In the presence of volatile organic compounds, the equilibrium favours the formation of higher levels of ozone. Background levels of ozone, mainly of anthropogenic origin, are in the range 40–70 $\mu g/m^3$ (0.02–0.035 ppm) but can be as high as 120–140 $\mu g/m^3$ (0.06–0.07 ppm) for 1 hour. In Europe, maximum hourly ozone concentrations may exceed 300 $\mu g/m^3$ (0.15 ppm) in rural areas and 350 $\mu g/m^3$ (0.18 ppm) in urbanized regions. Submaximal levels (80–90% of maximum) can occur for 8–12 hours a day for many consecutive days.

Ozone toxicity occurs in a continuum in which higher concentrations, longer exposure duration and greater activity levels during exposure cause greater effects. Short-term acute effects include respiratory symptoms, pulmonary function changes, increased airway responsiveness and airway inflammation. These health effects were statistically significant at a concentration of 160 $\mu g/m^3$ (0.08 ppm) for 6.6-hour exposures in a group of healthy exercising adults, with the most sensitive subjects experiencing functional decrements of > 10% within 4–5 hours. Controlled exposures of heavily exercising adults or children to an ozone concentration of 240 $\mu g/m^3$ (0.12 ppm) for 2 hours have also been observed to produce decrements in pulmonary function. There is no question that substantial acute adverse effects occur with 1 hour of exercising exposure at concentrations of 500 $\mu g/m^3$ or higher, particularly in susceptible individuals or subgroups.

The selection of guidelines for ambient ozone concentrations is complicated by the fact that detectable responses occur at or close to the upper limits of background concentrations. At ozone levels of 200 $\mu g/m^3$ and lower (for exposure periods of 1–8 hours) there are statistically significant decrements in lung function, airway inflammatory changes, exacerbations of respiratory symptoms and symptomatic and functional exacerbations of asthma in exercising susceptible people. Functional changes and symptoms as well as increased hospital admissions for respiratory causes are also observed in population studies. Selection of a guideline has to be based on the premise that some detectable functional responses are of little or no health concern, and that the number of responders to effects of concern is too few to represent a group warranting protection from exposures to ambient ozone.

A guideline value for ambient air of 120 $\mu g/m^3$ for a maximum period of 8 hours per day has been established as a level at which acute effects on public health are likely to be small.

The second edition of the WHO air quality guideline (WHO 2000) [41] set the guideline value for ozone at 120 $\mu g/m^3$ for an 8-hour daily average. Since the mid-1990s there has been no major addition to the evidence from chamber studies or field studies. There has however been a marked increase in health effects evidence from epidemiological time-series studies. Combined evidence from those studies show convincing, though small, positive associations between daily mortality and ozone levels, independent of the effects of particulate matter. Evidence from both chamber and field studies also indicate that there is considerable

individual variation in response to ozone. In view of these considerations, there is a good case for reducing the guideline from the existing level of 120 μg/m$^3$. It is recommended that the air quality guideline for ozone is set at the level of 100 μg/m$^3$ for daily maximum 8-hour mean [69].

*Particulate matter*

It seems that in northern Europe, $PM_{10}$ levels (particulate matter in which 50% of particles have an aerodynamic diameter of less than 10 μm) are low, with winter averages even in urban areas not exceeding 20–30 μg/m$^3$. In Western Europe, levels seem to be higher at 40–50 μg/m$^3$, with only small differences between urban and non-urban areas. Levels in some central and eastern European locations from which data are available appear nowadays to be only a little higher than those measured in cities such as Amsterdam and Berlin. As a result of the normal day-to-day variation in $PM_{10}$ concentrations, 24-hour averages of 100 μg/m$^3$ are regularly exceeded in many areas in Europe, especially during winter inversions.

The weight of evidence from numerous epidemiological studies on short-term responses points clearly and consistently to associations between concentrations of particulate matter and adverse effects on human health at low levels of exposure commonly encountered in developed countries. The database does not, however, enable the derivation of specific guideline values at present. Most of the information that is currently available comes from studies in which particles in air have been measured as $PM_{10}$. There is now also a sizeable body of information on fine particulate matter ($PM_{2.5}$) and the latest studies are showing that this is generally a better predictor of health effects than $PM_{10}$. Evidence is also emerging that constituents of $PM_{2.5}$ such as sulfates are sometimes even better predictors of health effects than $PM_{2.5}$ per se.

The large body of information on studies relating day-to-day variations in particulate matter to day-to-day variations in health provides quantitative estimates of the effects of particulate matter that are generally consistent. The available information does not allow a judgement to be made of concentrations below which no effects would be expected. Effects on mortality, respiratory and cardiovascular hospital admissions and other health variables have been observed at levels well below 100 μg/m$^3$, expressed as a daily average $PM_{10}$ concentration. For this reason, no guideline value for short-term average concentrations is recommended either. Risk managers are referred to the risk estimates provided in the tables for guidance in decision-making regarding standards to be set for particulate matter.

The body of information on long-term effects is still smaller. Some studies have suggested that long-term exposure to particulate matter is associated with reduced survival, and a reduction of life expectancy in the order of 1–2 years. Other recent studies have shown that the prevalence of bronchitis symptoms in children, and of reduced lung function in children and adults, are associated with particulate matter exposure. These effects have been observed at annual average concentration levels below 20 μg/m$^3$ (as $PM_{2.5}$) or 30 μg/m$^3$ (as $PM_{10}$). For this reason, no guideline value for long-term average concentrations is recommended. Risk managers are referred to the risk estimates provided in the tables for guidance in decision-making regarding standards to be set for particulate matter.

*Sulfur dioxide*

In Western Europe and North America, concentrations of sulfur dioxide in urban areas have continued to decline in recent years as a result of controls on emissions and changes in fuel use. Annual mean concentrations in such areas are now mainly in the range 20–60 μg/m$^3$ (0.007–0.021 ppm), with daily means seldom more than 125 μg/m$^3$ (0.044 ppm).

*Short-term exposures*
Controlled studies with exercising asthmatics indicate that some asthmatics experience changes in pulmonary function and respiratory symptoms after periods of exposure as short as 10 minutes. Based on this evidence, it is recommended that a value of 500 μg/m$^3$ (0.175 ppm) should not be exceeded over averaging periods of 10 minutes. Because exposure to sharp peaks depends on the nature of local sources, no single factor can be applied to this value in order to estimate corresponding guideline values over somewhat longer periods, such as an hour.

*Exposure over a 24-hour period and long-term exposure*
Day-to-day changes in mortality, morbidity or lung function related to 24-hour average concentrations of sulfur dioxide are necessarily based on epidemiological studies in which people are in general exposed to a mixture of pollutants, which is why guideline values for sulfur dioxide have previously been linked with corresponding values for particulate matter.

This approach led to a previous guideline value of 125 μg/m$^3$ (0.04 ppm) as a 24-hour average. In more recent studies, adverse effects with significant public health importance have been observed at much lower levels of exposure. The following guidelines are recommended [69]:

24 hours: 20 μg/m$^3$
10 minute: 500 μg/m$^3$

### 5.1.4. Indoor air pollutants

*Environmental tobacco smoke*

Environmental tobacco smoke (ETS) is a dynamic complex mixture of thousands of compounds in particulate and vapour phases, and cannot be measured directly as a whole. Instead, various marker compounds, such as nicotine and respirable suspended particulates (RSPs), are used to quantify environmental exposure.

ETS has been found to be carcinogenic in humans and to produce a substantial amount of morbidity and mortality from other serious health effects at levels of 1–10 $\mu g/m^3$ nicotine (taken as an indicator of ETS). Acute and chronic respiratory health effects on children have been demonstrated in homes with smokers (nicotine 1–10 $\mu g/m^3$) and even in homes with occasional smoking (0.1–1 $\mu g/m^3$). There is no evidence for a safe exposure level [41].

*Man-made vitreous fibres*

Airborne concentrations during the installation of insulation comprising man-made vitreous fibres (MMVF) are in the range $10^5$–$2 \cdot 10^6$ fibres/$m^3$, which is generally higher than the concentrations of about $10^5$ fibres/$m^3$ reported for production plants. Little information is available on ambient concentrations of MMVF. A few limited studies of MMVF in outdoor air have reported concentrations ranging from 2 fibres/$m^3$ in a rural area to $1.7 \cdot 10^3$ fibres/$m^3$ near a city. These levels are estimated to represent a very small percentage of the total fibre and total suspended particulate concentrations in the ambient air.

The deep lung penetration of various MMVF varies considerably, as a function of the nominal diameter of the material. For the six categories of MMVF considered here (continuous filament fibre glass, glass wool fibres, rock wool fibres, slag wool fibres, refractory ceramic fibres and special purpose fibres (glass microfibers), the potential for deep lung penetration is greatest for refractory ceramic fibres and glass microfibers; both of these materials are primarily used in industrial applications.

For most MMVF, available data are considered inadequate to establish air quality guidelines. No safe exposure level is recommended [41].

*Radon*

Exposure to radon and radon progeny is the dominant source of exposure to ionizing radiation in most countries. The radon levels vary considerably between dwellings, and depend primarily on the inflow of soil gas and the type of building material. Arithmetic mean concentrations in European countries range from about 20 Bq/$m^3$ to 100 Bq/$m^3$, with even higher levels in some regions. The geometric mean concentrations are generally about 20–50% lower because of the skewed distribution of radon levels.

Radon is a known human carcinogen with genotoxic action. Recent case-control studies provide evidence on lung cancer risks related to residential radon exposure. In general, the exposure assessment was based on radon measurements in the homes of the people being studied, covering residential periods of about 10–30 years. Some of the studies indicate

increased relative risks for lung cancer by estimated time-weighted residential radon level or cumulative exposure.

Current levels of radon in dwellings and other buildings are of public health concern. No guideline value for radon concentration is recommended. Nevertheless, the risk can be reduced effectively based on procedures that include optimization and evaluation of available control techniques. In general, simple remedial measures should be considered for buildings with radon progeny concentrations of more than 100 $Bq/m^3$ equilibrium equivalent radon as an annual average, with a view to reducing such concentrations wherever possible.

### 5.1.5. Bioaerosols

Bioaerosols are airborne particles composed of or derived from organisms. The bioaerosols that are discussed in this report include bacteria, fungi, viruses, plants, and animals.

*Bacteria*

Bacteria are single celled organisms that have a cell membrane but not a nucleus or membrane bound organelles. Bacteria can be classified into four groups based on their preferred temperature range. Of most interest in the indoor environment are the mesophilic bacteria. In the indoor environment, the majority of bacteria in the air come from human and pet sources, such as human skin and respiratory tracts. The air concentrations of these bacteria depend on the number of people, their activity levels, the type of clothing, and the ventilation rates of the space. The risk from environmental bacteria increases when excessive concentrations are found indoors. Most naturally occurring bacteria do not cause negative human health effects. However, some bacteria can cause negative human health effects. Of prime interest to indoor air quality are the bacterial aerosols, which can be inhaled.

Health effects from exposure to bacteria can be caused by four mechanisms: infection, hypersensitivity pneumonitis, toxins, and VOCs. Infection is the best known mechanism and is normally acquired through inhalation. Bacteria are transmitted through the air from humans or other animals. Examples of bacterial infections include legionellosis, tuberculosis, anthrax, and brucellosis.

Bacteria produce exo-toxins and endo-toxins. Exo-toxins are released into the bacteria's environment. Exo-toxins have not been reported in air. Endo-toxins are part of the bacteria's cell wall. Low exposures are considered necessary for developing the immune system. Higher exposures of endo-toxins may produce mucous membrane irritation. Very high exposures can produce flu-like symptoms with high fever and difficulty breathing.

Bacteria can produce VOCs. Some of these compounds have distinctive odours, which is associated with the decomposition of material. Exposure to VOCs may be a cause of sick building syndrome. However, there is little evidence to connect bacteria produced VOCs to specific health effects.

*Fungi*

Fungi are a group of organisms which have cell walls that enclose a nucleus, lack chlorophyll and have no vascular structure. They can consist of single cell or they can be multi-cellular organisms. Fungi appear in a variety of forms, from mushrooms to mildew. The simplest classification of fungi is by visual inspection. Mould is a term used for visible fungal growth where it is not wanted and has no taxonomic significance. Mildew is the term used for fungi growing on windowsills, fabrics, or bathroom tile.

Fungi require adequate temperatures, moisture levels, nutrients, light, and atmosphere to grow. For each fungus there is a range of temperature, moisture levels, nutrients, light, and atmosphere which is acceptable. Consequently, there is no one set of environmental

conditions for optimal fungus growth and a variety of environmental conditions in which fungi can grow.

Fungi can cause human health problems. Fungi are a human health concern from three perspectives: first, they can be a source of allergens; second, they are a source of particles, and third, they can release toxins. Generally, infectious diseases from fungi only establish in human hosts with compromised immune systems. It is impossible to eliminate all sources of fungi from the indoor environment.

Indoor/outdoor relationships should be assessed by comparing both the concentration and the type of species composition present. Indoor fungal concentrations that are consistently and significantly higher than outdoor concentration may indicate that indoor sources are present.

*Viruses*

Viruses are replicating, non-cellular particles that contain only one type of nucleic acid (DNA or RNA) and depend completely on their hosts for reproduction. Viruses cause only infectious diseases. Nearly all viruses are transmitted between two humans, although a few viruses can be transmitted between animals and humans.

Most viruses are spread through the air, which is a relatively hostile environment for the virus. Viruses tend to sorb onto other particles for transportation. The combined particle may use several points of entrance to the human system; respiratory tract, mucous membranes, gastrointestinal tract, skin, and open wounds. In order to cause infection, the virus must reach the cells that it will infect, which can be prevented by the body's natural defence mechanisms.

The risk of disease associated with exposure depends on individual immune function, viral virulence and concentration, and particle size. Building factors that may influence viral infection are temperature, relative humidity, density of population, and ventilation rates. Some viruses demonstrate seasonal variations due to length of time spent indoors, reduced fresh air rates, and increased tightness of the building envelope.

### *Plant and Animal Matter*

Plant and animal matter make up a large portion of airborne environmental allergens. Dust mites, animal dander, pollen, fungi, bird faeces, and cockroaches have been identified as allergens of particular concern in the indoor environment.

House dust mites have been studied extensively and are shown to be a major allergen. Dust mites are members of the spider family and use discarded human skin as a food source. Consequently, bedding material tends to have high concentrations of dust mites, dried body parts and faecal matter. Dust mite population growth is faster under increasing relative humidity levels.

Animal dander or skin cells, is one of the major sources of allergenic matter from furred animals such as cats, dogs, horses and cows. Other animal allergens include saliva and urine.

Pollen grains can be generated from outdoor plants, which have infiltrated the building, and indoor plants. Rhinitis, inflammation of the nasal membranes, is a prevalent symptom of a

pollen allergy because of the preferential deposition of pollen in this area. Indoor pollen concentrations vary with outdoor concentrations unless there is an indoor source. Most pollen related reactions can be anticipated because outdoor pollen generation is seasonal.

Bird allergens are found in feathers and droppings. Highest exposure to avian material is associated with cleaning birdcages, lofts and coops.

Cockroaches produce several allergens; faecal matter, saliva, and dried body fragments. The cockroach can survive low ambient humidity conditions because it can actively search for water. However, cockroaches prefer moist conditions with readily available food sources. Consequently, cockroaches are found in unsanitary conditions and are associated with kitchens, animal care facilities, and bathrooms.

*Exposure guidelines*

A brief evaluation focusing on the exposure and health risk for building users has been presented. In non-industrial indoor environments, the most important source of airborne bacteria is the presence of humans [70]. In particular activities like talking, sneezing, coughing, walking, washing and toilet flushing can generate airborne biological particulate matter. Food stuffs, house plants and flower pots, house dust, pets and their bedding, textiles, carpets, wood material and furniture stuffing, occasionally release spores of Alternaria, Aspergillus, Botrytis, Cladosporium, Penicillium, Scopulariopsis into the air [71] [72].

Although indoor environments are considered to be protective, they can become contaminated with particles that present different and sometimes more serious risks than those related to outdoor exposures, when their concentrations exceed recommended maximum limits. The National Institute of Occupational Safety and Health (NIOSH) recommends 1000 colony-forming units per $m^3$ [CFUs/$m^3$] for the total number of bioaerosol particles [73]. Moreover, the American Conference of Governmental Industrial Hygienists (ACGIH) recommends a maximum of 1000 CFUs/$m^3$ for the total number of bioaerosol particles, with the culturable count for total bacteria not to exceed 500 CFUs/$m^3$ [74].

Numerical guidelines for exposure to specific bioaerosols are currently lacking for the following reasons:

- Incomplete data on concentrations and types of microbial particulate indoors, especially as affected by geographical, seasonal, and type-of-building parameters.
- Absence of data relating bioaerosol exposure to building related illness.
- Enormous variability in kinds of microbial particulate including viable cells, dead spores, toxins, antigens, and viruses.
- Large variability in human susceptibility to microbial particulate, making estimates of health risk difficult.

## 5.2. Performance Indicators for Indoor Air Quality

The indoor air contaminants presented in Section 5.1 could all serve as performance indicators for the indoor air quality in a building. In addition, performance indicators specifically focusing on the ventilation of the building could be developed, for example air change rate, ventilation efficiency, contaminant removal efficiency, etc.). . The determination of the air change rate in a single zone as induced by weather conditions or mechanical ventilation is described in the international standard ISO 12569-2000 [75]. In this section, the applicability of the air change rate as a performance indicator, which replaces the indicators presented in Section 5.1, is presented (Section 5.2.1). Furthermore, an indicator framework for indoor air quality has been developed by Schuh [42]. The results from this study are summarized in Section 5.2.2.

### 5.2.1. Air change rate

In this report, it is the objective to develop a direct mapping from the set of system indicators/parameters to some set of performance indicators (PI's). Unambiguous (normative) statements of how observable variables result in a particular quantification of the PI (e.g. a rating, score or real number) are defined. Such a normative approach rules out any bias and guarantees that the results are indicative and objective indicators of a certain performance aspect.

The applicability of the air change rate of a room as a performance indicator for indoor air quality is questioned based on several reasons. First of all, the air change rate is not considered to be a suitable performance indicator, since it may be difficult to assign an objective value to the indicator. The minimum air change rate of a room, which is defined in the building standard, depends on the function of the room in a building. Normative assessment of the air change rate may therefore not be straightforward.

Second, minimum air change rates for specific rooms are defined by the building standard. In a previous study [76], air change rates and indoor air contaminant concentrations (nitrogen dioxide ($NO_2$) and formaldehyde) were determined in a study of 96 homes. The study showed that $NO_2$ concentrations in homes were positively correlated with air change rates (indicating a significant contribution of outdoor sources to indoor levels). Moreover, nitrogen dioxide concentrations were significantly elevated in homes equipped with gas stoves and, to a lesser extent, in homes with gas heating systems. Formaldehyde concentrations were negatively correlated with air change rates and were significantly elevated in homes heated by electrical systems, in those with new wooden or melamine furniture, and in those where painting or varnishing had been done. In addition, it has been indicated by other studies [77] as well that, while ventilation effectively decreases formaldehyde concentrations, some categories of buildings such as those with new off-gassing sources and heated by electrical baseboard heaters may require a higher air change rate compared to the minimum air change rate in the building standard, in order to keep the formaldehyde levels within the corresponding guidelines.

In general, if the air change rate of a room/building does meet the minimum required air change rate that is defined in the building standard for ventilation, it does not necessarily mean that all indoor contaminant concentrations lie in an acceptable range below the required guidelines [78]. It is therefore recommended to use indoor contaminant concentrations as

performance indicators for indoor air quality, instead of the air change rate as a main performance indicator.

### 5.2.2. Indicator framework for indoor air quality

An intensive list of indoor air contaminants is presented in Section 5.1. In principle, the guidelines for each contaminant could serve as a performance indicators or parameter for indoor air quality. Though, this would result in a long and complex list of indicators/parameters, which may not be very practical and useful for building design and building management. The study reported by Schuh [42] has investigated this issue previously.

Performance indicators for indoor air quality have been studied previously by Schuh [42], and from this study [42] it has been concluded that a performance indicator list should be practical and useful for building designers and building managers. Schuh developed a set of indicators, based on IAQ data, which provided management with pertinent information for decision making. IAQ indicators were developed using a case study methodology, which helped to ensure that the indicators were applicable. The IAQ indicators were verified by a survey of building managers across Canada. The results of the survey validated the appropriateness and usefulness of the set of IAQ indicators.

Starting from a relatively long and complex list for IAQ performance indicators, consisting of guidelines for the contaminant concentrations presented in Section 5.1 and performance indicators for thermal comfort (Section 6), the list of performance indicators for indoor air quality was reduced to six indicators: Effective temperature, effective ventilation, combustion infiltration, odour intensity, and particulate matter. Table 11 presents the performance indicator list which has been developed by Schuh [42].

Table 11: Performance indicators for indoor air quality [42]

| Performance Indicator | Indicator/Parameter | Guideline |
|---|---|---|
| Effective Temperature | Temperature and relative humidity | ASHRAE Standard 55 [79] |
| Effective Ventilation | Carbon Dioxide | 1000 ppm |
| Combustion Infiltration | Carbon Monoxide | 10 ppm |
| Odour intensity | Intensity and Character | - |
| Particulate matter | Total mass of particles > 2.5μm | 40 $\mu m/m^3$ |

Temperature and relative humidity were combined into one indicator called effective temperature. The effect which relative humidity has on the perception of temperature is widely recognized. The appropriate ranges of temperature and relative humidity are evaluated based on the ASHRAE Standard 55 on thermal environmental conditions for human occupancy [79]. The effective temperature indicator is assessed by measurement of the temperature and relative humidity and determination if the value lies within the specified comfort range. Other factors or models, such as the PMV model, were deemed too complex to be used regularly. Moreover, ASHRAE's effective temperature involving operative temperature, wet skin fraction, moisture permeability index, water vapour pressure in ambient air, and the saturated vapour pressure at the effective temperature, was also deemed too complicated for the purposes of the IAQ indicator set but may be useful in special circumstances [42].

Carbon dioxide was considered as an appropriate air quality measurement not because of its potential to be a contaminant, although it can be, but because of its potential to predict the

amount of outdoor air supplied to a space. Natural background levels range from 350 to 500 ppm. ASHRAE suggests that a level of 1000 ppm or 650 ppm above ambient levels would be equivalent to a delivery rate of 10 l/s per person of outside air. This delivery rate would be acceptable for most applications in the institution [43]. Levels of carbon dioxide are measured in a space after the environment is in equilibrium to determine if concentrations are below 1000 ppm during occupied periods.

Carbon monoxide was determined to be an appropriate air quality measure because of the significance of the health effects and associated risk and liability of this contaminant. Sources of carbon monoxide are carbon based heat sources. Additionally, if there are other potential sources of carbon monoxide within the buildings, such as smoking areas and heating systems, a carbon monoxide indicator assists in identifying any IAQ problems in these areas. A carbon monoxide indicator measures carbon monoxide concentrations and determines if the concentrations are below the 10 ppm standard [41].

Odour is a subjective measurement and olfactory sensitivity is affected by hormonal factors, sex, certain diseases, and various drugs. Despite the complications of judging odours, it remains a valuable tool for diagnosing potential IAQ problems. Many times, odour is the first indication of an IAQ problem. Odour has four attributes: detectability, intensity, character, and hedonic tone. Detectability refers to the minimum concentration that provokes an olfactory sensation in a specified segment of the population. Intensity refers to the strength of the sensation. Character is a qualitative description of the odour. Hedonic tone is the degree the odour is perceived as pleasant or unpleasant. It is assumed that if there is an IAQ concern that involves odour that it is detectable and undesirable.

Particulates are defined as suspended mixtures of solid of liquid particles. They include asbestos, silica dust, coal dust, bioaerosols, smoke, and fumes. The toxicity of particles is related to the size and nature of the particle. Smaller particles are deposited further into the lungs and the removal processes at this location are slow. Particles less than 3 $\mu$m (microns) are of concern. Indoor air quality standards are available for total mass particle measurements. The particulate indicator would measure total mass of particles > 2.5 $\mu$m to determine if the quantity of particles is less than 40 $\mu m/m^3$.

In summary, Table 11 presents the list of IAQ performance indicators developed by Schuh [42]. The measurements required to implement these indicators are simple to conduct and it is relatively inexpensive to obtain or rent the equipment. Appropriate guidelines are available for all but one of the indicators. Odour intensity indicator is used to monitor the reoccurrence of IAQ problems, identify potential sources, and follow infiltration paths. Although this indicator is the least objective, it may be the most valuable at identifying potential IAQ problems before they become a concern. The combination of indicators can assist with many IAQ concerns. Early diagnosis of mould growth could be detected by increasing particulate load (spores) and unusual odours (VOCs). Determining the cause of mucous membrane irritation could be determined by examining the effective temperature (low relative humidity), particulate load (increasing levels of particles), or odour intensity (VOC exposure). Ensuring satisfactory mitigation measures are in place for renovations could be determined by the particulate load or odour intensity indicators.

## 5.3. Conclusion

The analysis showed that the indoor air quality in a building is determined by chemical components which are present in the indoor environment, such as organic pollutants, inorganic pollutants, classical and indoor air pollutants. The Core Indicator Indoor Air Quality is characterized by these (four) Performance Indicators.

Each Performance Indicator is dependent of the specific indicators or parameters (pollutants). Table 12 presents the performance indicators and related indicators/parameters for indoor air quality.

Table 12: Performance Indicators for Indoor Air Quality

| Performance Indicator | Indicator/Parameter | Guideline |
|---|---|---|
| Organic pollutants | Acrylonitrile | As low as possible |
| | Benzene | As low as possible |
| | Butadiene | No guideline value available |
| | Carbon disulfide | ≤ 100 µg/m$^3$ |
| | Carbon monoxide | ≤ 100 mg/m$^3$ (90 ppm) for 15min<br>≤ 60 mg/m$^3$ (50 ppm) for 30min<br>≤ 30 mg/m$^3$ (25 ppm) for 1h<br>≤ 10 mg/m$^3$ (10 ppm) for 8h |
| | 1,2-Dichloroethane | ≤ 0.7 mg/m$^3$ |
| | Dichloromethane | ≤ 3 mg/m$^3$ |
| | Formaldehyde | ≤ 0.1 mg/m$^3$ as a 30-min average |
| | Polycyclic aromatic hydrocarbons | As low as possible |
| | Polychlorinated biphenyls | No guideline value available |
| | Polychlorinated dibenzodioxins and dibenzofurans | No guideline value available |
| | Styrene | ≤ 0.26 mg/m$^3$ (weekly average) |
| | Tetrachloroethylene | ≤ 0.25 mg/m$^3$ |
| | Toluene | ≤ 1 mg/m$^3$ as a 30-min average |
| | Trichloroethylene | As low as possible |
| | Vinyl chloride | As low as possible |
| Inorganic pollutants | Arsenic | As low as possible |
| | Asbestos | As low as possible |
| | Cadmium | ≤ 5 ng/m$^3$ |
| | Chromium | As low as possible |
| | Fluoride | ≤ 1 µg/m$^3$ |
| | Hydrogen sulfide | ≤ 7 µg/m$^3$ as a 30-min average |
| | Lead | No guideline value available |
| | Manganese | ≤ 0.15 µg/m$^3$ |
| | Mercury | ≤ 1 µg/m$^3$ |
| | Nickel | No guideline value available |

| | | |
|---|---|---|
| | Platinum | No guideline value available |
| | Vanadium | ≤ 1 μg/m$^3$ |
| Classical pollutants | Nitrogen dioxide | ≤ 40 μg/m$^3$ |
| | Ozone and other photochemical oxidants | ≤ 100 μg/m$^3$ |
| | Particulate matter | No guideline value available |
| | Sulfur dioxide | 24 hours: 20 μg/m$^3$<br>10-min: 500 μg/m$^3$ |
| Indoor air pollutants | Environmental tobacco smoke | As low as possible |
| | Man-made vitreous fibres | As low as possible |
| | Radon | As low as possible |
| Bioaerosols | | Total number of bioaerosol particles < 1000 CFUs/m$^3$<br>Culturable count for total bacteria < 500 CFUs/m$^3$ |

The applicability of the air change rate of single rooms as an independent performance indicator for indoor air quality has been discussed. It has been recommended to use indoor contaminant concentrations as performance indicators for indoor air quality, instead of the air change rate as a main performance indicator, since an air change rate of a room/building which meets the minimum required air change rate that is defined in the building standard, does not necessarily guarantee that all indoor contaminant concentrations lie in an acceptable range below the required guidelines.

Incorporation of the list of performance indicators (Table 12) in a framework may result in a long and complex list of indicators/parameters, which may not be very practical and useful for building design and building management. It is recommended to use a relatively short and simple list of performance indicators to ensure that these indicators are applicable. For example, a list of performance indicators developed by Schuh [42] could be applied.

# 6. QUALITY OF DRINKING WATER

General drinking-water safety is assured by maintenance protocols, regular cleaning, temperature management and maintenance of a disinfectant residual. The drinking water supplier is responsible for these aspects. However, responsibility for many actions essential to the control of drinking-water quality in buildings may be outside the responsibility of the drinking-water supplier. Significant contamination can occur because of factors within the built environment, and specific requirements in the building environment (including hospitals and health care facilities) are distinct from those in the domestic environment. For these reasons, authorities responsible for building safety should be responsible for developing and implementing water safety plans (WSPs) [80]. Regulatory or other appropriate authorities may provide guidance on the development and application of WSPs for (large) building drinking-water systems, which should be implemented by managers.

This section presents the performance indicators to maintain the quality of drinking water in buildings. In the analysis, it is assumed that safe drinking water is supplied to the building, while the manager of the building is responsible for the control of the drinking-water quality in the building.

The principal hazards that may accrue in the drinking-water systems of (large) buildings are ingress of microbial contamination (which may affect only the building or also the wider supply), proliferation and dispersal of bacteria growing on water contact surfaces (especially Legionella) and addition of chemical substances from piping, jointing and plumbing materials [80].

Faecal contamination may occur through cross-connection and backflow and from buried/immersed tanks and pipes, especially if not maintained with positive internal water pressure.

Legionella bacteria are the cause of legionellosis, including legionnaire's disease. They are ubiquitous in the environment and can proliferate at temperatures experienced at times in piped distribution systems. The route of infection is by inhalation of droplets or aerosols; however, exposure from piped water systems is preventable through the implementation of basic water quality management measures, including maintaining water temperature outside the range at which Legionella proliferates 25-50 $^{o}$C and maintaining disinfectant residuals throughout the piped distribution system.

## 6.1. Legionella

Legionella are heterotrophic bacteria found in a wide range of water environments and can proliferate at temperatures above 25 °C. Legionella are members of the natural flora of many freshwater environments, such as rivers, streams and impoundments, where they occur in relatively low numbers. However, they thrive in certain human-made water environments, such as water cooling devices (cooling towers and evaporative condensers) associated with air conditioning systems, and hot water distribution systems, which provide suitable temperatures and conditions for their multiplication. Devices that support multiplication of Legionella have been associated with outbreaks of Legionnaires disease. Legionella survive and grow in biofilms and sediments and are more easily detected from swab samples than from flowing water.

The most common route of infection is the inhalation of aerosols containing the bacteria. Such aerosols can be generated by contaminated cooling towers, warm water showers, humidifiers and spas. Aspiration has also been identified as a route of infection in some cases associated with contaminated water, food and ice. There is no evidence of person-to-person transmission.

The detection of Legionella bacteria requires specialist laboratory techniques. Routine monitoring for aerobic bacteria can be used as an indication of whether microbiological control is being achieved. In general, these monitoring techniques include routine sampling and testing for the presence of bacteria, both general (aerobic) bacterial species and Legionella bacteria. However, it should be noticed that sampling and testing is a relatively intensive method to monitor the presence of legionella in a system. Sampling and legionella detection requires microbiological analysis and specialist laboratory techniques. As an alternative, building engineers and managers could focus on the prevention of legionella in the buildings' water system. Since the detection of legionella based on microbiological sampling is considered to be a method which is too intensive/expensive for the inclusion in a performance indicator framework, the analysis focuses on methods to prevent the development of legionella in the drinking water system of a building.

*Legionella Prevention*

Owing to the prevalence of Legionella, the potential for ingress into drinking-water systems should be considered as a possibility, and control measures should be employed to reduce the likelihood of survival and multiplication. Disinfection strategies designed to minimize biofilm growth and temperature control can minimize the potential risk from Legionella.

The organisms are sensitive to disinfection. Monochloramine has been shown to be particularly effective, probably due to its stability and greater effectiveness against biofilms. Water temperature is an important element of control strategies. Wherever possible, water temperatures should be kept outside the range of 25-50 °C. In hot water systems, storages should be maintained above 55 °C, and similar temperatures throughout associated pipe work will prevent growth of the organism [81].

Where temperatures in hot or cold water distribution systems cannot be maintained outside the range of 25-50°C, greater attention to disinfection and strategies aimed at limiting development of biofilms is required. Accumulation of sludge, scale, rust, algae or slime deposits in water distribution systems supports the growth of Legionella, as well as stagnant water does. Systems that are kept clean and flowing are less likely to support excess growth of Legionella. Care should also be taken to select plumbing materials that do not support microbial growth and the development of biofilms.

Fundamentally, the responsibility for managing the risk of legionellosis belongs to the owner or manager responsible for the potable water or in-building distribution system. To ensure prevention of legionellosis a water safety plan should be developed and properly implemented. Table 13 presents an exemplary water safety plan for an in-building water distribution system.

Table 13: Water safety plan for in-building water distribution system [81].

| Process step | Water source and receipt | In building | | | |
|---|---|---|---|---|---|
| | | Storage | Distribution | Hot water | Consumer |
| Assess hazards and prioritize risks | Low disinfection residual leading to presence of legionella in received water | Elevated temperature causing proliferation of legionella | Entry of nutrients through sullage (grey water, sewage, etc.), providing growth source for legionella | Temperatures of 25–50°C, leading to proliferation of legionella | High-aerosol generating devices causing potential for inhalation of legionella |
| Identify control measures | Water supplier to meet health-based water standards Water guidelines to be based on national guidance and/ or liaison with the health department | Temperature to be below 25°C for cold-water storage | Backflow to be prevented | Minimum flow temperature of 60°C to be maintained in water leaving the heating unit, and of 50°C at the tap (1 minute after leaving the heating device | No high aerosol generating devices to be in place after two years (to be replaced by low-aerosol generating devices) |
| Monitor control measures | Agreement between water authority and user; legionella levels in source water to be checked periodically | Plumbing staff to check temperature monthly by thermometer and surface probe | Plumbing staff to check backflow prevention devices annually | Plumbing staff to check temperature monthly by thermometer and surface probe at sentinel points | Point-of-use treatment unit agreement with contractors; building maintenance supervisor to oversee contract and audit every 6 months |
| Prepare management procedures | Water authority to immediately communicate any deviations in agreed water quality to user and to health department | Storage tank to be isolated and temperature problem addressed | Backflow prevention devices to be replaced if not working; system to be super-chlorinated; communication protocol to be followed | Water source to be isolated if possible and source disinfected; and temperature problem addressed | Water source to be isolated if possible and source disinfected |
| Develop supporting programmes | Staff training and education; maintenance and calibration; backflow and plumbing controls | | | | |

*Legionella Control*

The focus of attention in managing legionella risks should be on preventing both proliferation and exposure, in line with the approach that forms part of a water safety plan. Regarding the control measures for legionella the following performance indicators have been identified:

- Water quality and treatment: Water from the supplier should meet the appropriate drinking-water standards or guidelines [80] of the jurisdiction, and should not contain high levels of nutrients.
- Distribution systems: Pipes should be as short as possible. In complex systems, regulating valves should be used to control flow. Dead ends should be avoided in both the design and construction phases, and in existing systems they should either be removed or regularly flushed. Standard system fittings should include devices to prevent backflow on heat production systems, and purge valves to prevent scaling and corrosion and facilitate monitoring.
- Construction materials: The materials used to construct piped water distribution systems should be compatible with the chemical quality of water (after a corrective treatment) and should minimize bacterial growth.
- Disinfection: to control legionella numbers in the distribution system, a disinfectant residual should be maintained. Monochloramine residual (currently available only for mains distribution systems) appears to be effective against legionella in biofilms, and may be more effective than chlorine.
- Biofilms: Routine cleaning of storages and control of nutrients in source water will reduce nutrient load and so help to reduce biofilm formation and growth.
- Temperature: Temperature is critical in legionella control. Consequently, water temperature should, as far as possible, be measured and registered.

Hospitals, nursing care homes, other health care facilities, schools, hotels and some other large buildings are high-risk environments, because of both the complex nature of their drinking-water systems and the sensitivities of their occupants. Requirements similar to those outlined above for other large buildings apply, but heightened vigilance in control measure monitoring and verification is generally justified.

For additional information on the prevention and control of legionella in in-building drinking-water systems the reader is referred to the publications of the World Health Organization on legionella [81].

## 6.2. Conclusions

The analysis showed that the quality of drinking water in a building is mainly determined by maintenance protocols, regular cleaning, temperature management and maintenance of a disinfectant residual, which are within the responsibility of the drinking water supplier. However, responsibility for many actions essential to the control of drinking-water quality in buildings is outside the responsibility of the drinking-water supplier. It has been demonstrated that ingress of microbial contamination, proliferation and dispersal of bacteria growing on water contact surfaces (especially legionella) and addition of chemical substances from piping, jointing and plumbing materials [80] are the principal hazards that may accrue in the drinking-water systems of (large) buildings.
The prevention and control of legionella in in-building water systems showed to be most critical with respect to the quality of drinking water [80]. Table 14 presents the performance indicators for maintaining drinking water quality in a building.

Table 14: Performance indicators for quality of drinking water

| Performance indicator | Description | Unit |
|---|---|---|
| Water safety plan (WSP) | A water safety plan is developed and implemented | [yes/no] |
| Water quality and treatment | Water from the supplier should meet the appropriate drinking-water standards or guidelines [80] | [yes/no] |
| Distribution systems | Pipes are as short as possible. Special valves, dead ends. | [yes/no] |
| Construction materials | Materials are compatible with the chemical quality of water and minimize bacterial growth | [yes/no] |
| Disinfection | Disinfectant residual are maintained | [yes/no] |
| Biofilms | Routine cleaning of storages and control of nutrients in source water | [yes/no] |
| Temperature | Measurement, registration and control of the water temperature ($T<25^{o}C$, $T>55^{o}C$) | [yes/no] |

# 7. THERMAL COMFORT

Human's thermal sensation is mainly related to the thermal balance of the body as a whole. This balance is influenced by physical activity and clothing, as well as the environmental parameters. Numerous indices for the assessment and design of thermal comfort conditions have been developed during the past 50 to 60 years. One of the most widely used indices in moderate thermal environments, the PMV index (predicted mean vote), predicts the mean value of the overall thermal sensation of a large group of persons as a function of activity (metabolic rate), clothing insulation, and the four environmental parameters: air temperature, mean radiant temperature, air velocity, and air humidity [84].

Alternatively, other methods for the assessment of moderate thermal environments could be used, such as the new effective temperature (ET) and the standard effective temperature (SET) [85]. These indices are based on a relatively simple model of the human body. Moreover, more advanced models are currently available that allow for the transient prediction of very detailed thermoregulatory parameters and, for some of the models, subjective responses to a wide range of environmental conditions [86].

Thermal comfort assessment includes a part of unambiguously defined performance indicators (PI) based on the notion of objectively quantifiable performance measures. The set of indicators is founded on existing knowledge in biophysics and physiology. Several researchers, such as [87], discussed the theoretical derivation of the indicators for the normative assessment of thermal comfort in buildings and their relevance in building design. In this section, Performance Indicators for the Thermal Comfort in a building are presented based on the models which are currently available.

## 7.1. Predicted Mean Vote

The predicted mean vote (PMV) is determined based on the estimated metabolic rate and the clothing insulation, and performance indicators: the measured or predicted air temperature, mean radiant temperature, relative air velocity, and air humidity. The PMV integrates the effects of the two personal parameters and the four environmental parameters on the thermal balance, and it predicts the mean thermal sensation on a seven-point thermal sensation scale.

Table 15 presents the seven-point thermal-sensation scale, which serves as a basis for the predicted mean vote. First of all, the Predicted Mean Vote model is based on two personal parameters: the metabolic rate of a person and the clothing insulation. Second, the Predicted Mean Vote is dependent of the Thermal Environment Parameters:

Table 15: Predicted Mean Vote

| | |
|---|---|
| 3 | Hot |
| 2 | Warm |
| 1 | Slightly warm |
| 0 | Neutral |
| -1 | Slightly cool |
| -2 | Cool |
| -3 | Cold |

### 7.1.1. Metabolic rate

The metabolic rate (M) is the rate of energy production of the body by metabolism, which varies with activity. Metabolic rate can be quantified by the met unit, where 1 met is defined as the metabolic rate of a sedentary person (seated, quiet); 1 met = 58.2 W/m$^2$. The unit W/m$^2$ refers to the area of the nude body.

Metabolic rate varies over a wide range, depending on the activity, the person, and the conditions under which the activity is performed. It can be very roughly assessed from knowledge of the occupation or from analysis of a task or activity. A more precise method, with an accuracy of around 20% (ISO/WD 8996-2004 [88]), involves observation of the activity and the use of tabulated values of metabolic rates for specific activities. The metabolic rate of a seated, relaxed person is designated to be 1 met, or 58.2 W/m$^2$, while the metabolic rate of this person is 3.4 met, or 200 W/m$^2$ while walking on a pace of 5 km/h.

The data for metabolic rate are based on measurement of metabolic rates (oxygen consumption) performed on human subjects continuously occupied with a specific activity. A detailed description of the evaluation and measurement of metabolic rate as well as a comprehensive collection of metabolic rates for typical activities can be found in ISO 8996-2004 [88].

### 7.1.2. Thermal Insulation of Clothing

Clothing insulation varies between occupants in a space due to differences in clothing preferences, company dress code, season, etc. Clothing insulation can be measured with a heated thermal manikin or with human subjects, but in practice, thermal comfort estimates based on tables may be sufficiently accurate. Additional information on the insulation provided by clothing ensembles composed of some typical combinations of garments can be found in ISO 7730-2005 [89]. If no matching clothing ensemble can be found in ISO 7730-2005 [89], tabulated insulation values of a wide variety of individual garments are provided in ISO 9920-2007 [90]. Summation of these partial insulation values for individual garments can be used as an estimate of the insulation of the entire clothing.

### 7.1.3. Thermal Environment Parameters

Measurement of the thermal parameters of the environment should be made in the occupied zones of the building at locations where the occupants are expected to spend their time, i.e., at their workstations or in seating areas. For the determination of PMV, the thermal parameters should be measured at the centre of gravity, which is 0.6 m for sedentary occupants and 1.1 m for standing activity. The PMV can also be measured directly by an integrating sensor.

Olesen (1995) [91], ISO 7726-2005 [92], and ASHRAE 55-1992R [79] provide detailed descriptions of the requirements for the measuring instrumentation and for thermal comfort measurement procedures. The PMV is expressed as a function of the personal parameters of metabolic rate and clothing insulation and the thermal environment parameters as input variables.

$$PMV = f(M, W, p_a, t_a, f_{cl}, t_{cl}, t_r, h_c)$$

with

$$t_{cl} = f(I_{cl}, f_{cl}, t_r, t_a)$$
$$h_c = f(t_{cl}, t_a, v_a)$$
$$f_{cl} = f(I_{cl})$$

where PMV is the predicted mean vote [-], M is the metabolic rate [W/m$^2$], W is the external work (zero for most indoor activities) [W/m$^2$], $f_{cl}$ is the ratio of the clothed surface area to the nude surface area [-],$I_{cl}$ is the thermal resistance of the clothing [ (m$^2$K)/ W], $t_a$ is the air temperature [$^o$C], $t_r$ is the mean radiant temperature [$^o$C], $v_a$ is the air velocity relative to the human body [m/s], $p_a$ is the partial water vapour pressure [Pa], $h_c$ is the convective heat transfer coefficient [W/(m$^2$K)], and $t_{cl}$ is the surface temperature of the clothing [$^o$C].

It is recommended to use the index only for PMV values in the range -2 to +2 , metabolic rates from 0.8 met to 4 met, clothing insulation from 0 clo to 2 clo, air temperatures from 10 to 30 C, mean radiant temperatures from 10 to 40 C, and relative air velocities from 0 to 1 m/sec. In non-air-conditioned buildings in warm climates, the occupants may sense warmth as being less severe than PMV predicts. For such buildings, an extension of the PMV model that includes an expectancy factor to account for this phenomenon has been introduced (Fanger and Toftum, 2002).

### 7.1.4. Predicted Percentage Dissatisfied

The PPD index (predicted percentage dissatisfied) is derived from the PMV index and predicts the percentage of thermally dissatisfied persons among a large group of people. The thermal sensation of humans is mainly related to the thermal balance of the body as a whole. Thermal balance exists when the internal heat production in the body is equal to the loss of heat to the environment. The studies underlying the PMV model showed that thermal sensation could be described as a function of the thermal load on the effector mechanisms of the human thermoregulatory system (vasodilatation, vasoconstriction, sweating, shivering). In the model, the thermoregulatory response has been related statistically to thermal-sensation votes collected from more than 1300 subjects.

Thermal dissatisfaction can be caused by a too warm or too cool overall thermal sensation. But even for a person who is thermally neutral for the body as a whole, thermal dissatisfaction may be the result of unwanted cooling or heating of local body parts. Separate indices exist for the assessment of the different types of local thermal discomfort.

Occupants of buildings are not alike, and therefore the individual thermal-sensation votes of the occupants of a given environment will be scattered around the mean. The PPD index predicts the number of people likely to feel uncomfortably warm or cool. When the PMV value is known, the PPD index can be calculated.

Typically, a 10% dissatisfaction criterion for whole-body thermal comfort is used for the determination of acceptable thermal conditions ([89] [79]). This corresponds to a PMV in the range -0.5 to +0.5. Note that the minimum attainable PPD is 5%, even when the result is a neutral thermal sensation (PMV = 0). Because of inter-individual differences, it is not possible to satisfy everyone.

The PMV index has been validated as a reliable predictor of thermal sensation in numerous comprehensive field studies in different climate regions during both summer and winter as

well as in a wide range of climate-chamber studies. However, in warm climates in buildings without air-conditioning, field studies have shown that the index predicts a warmer thermal sensation than the occupants actually feel. An extension of the PMV model for such buildings has now been proposed [93].

Inaccuracies in the methods for measuring thermal parameters and for estimating clothing insulation and metabolic rates may influence reliability. Individual differences between users of the index may to some extent affect the determination and interpretation of the index.

### 7.1.5. Local Thermal Discomfort

The PMV and PPD indices can be used to assess overall thermal comfort in a wide range of buildings and vehicles with differing HVAC (heating, ventilation, and air-conditioning) systems as well as for different combinations of activity, clothing habits, and environmental parameters. The indices are used widely for the evaluation and design of indoor thermal environments. In standards and guidelines, the indices are used to specify comfort criteria.

Thermal neutrality for the body as a whole is a necessary, but not sufficient, condition for thermal comfort. Local thermal discomfort due to draft, vertical temperature gradient, radiant asymmetry, or warm or cold floors may cause occupants to find the thermal conditions unacceptable. The most common cause of complaint is draft, which is defined as an unwanted, local cooling caused by air movement. Criteria to assess local thermal discomfort are provided in standards and guidelines [89] [79].

Local thermal discomfort may be caused by draught, vertical air temperature differences, a warm or cool floor, and radiant asymmetry. Regarding the discomfort due to draught, the percentage of people predicted to be bothered by draught is calculated by the draught rate (DR) [89]. Similarly, the percentage of people dissatisfied due to a relatively high temperature difference between head and ankles, a warm or cool floor, or dissatisfied by radiant temperature asymmetry is determined by calculation of the percentage dissatisfied (PD) [89].

### 7.1.6. Thermal environment

The desired thermal environment for a space may be selected from among three different categories defined by the standard [89]. Each category prescribes a maximum percentage dissatisfied for the body as a whole (PPD) and a PD for each of the four types of local discomfort. The categories of the thermal indoor environment are presented in Table 16.

Table 16: Categories of the thermal indoor environment ([89])

| Category | Thermal state of the body | | Local discomfort | | | |
|---|---|---|---|---|---|---|
| | PPD [%] | PMV | DR [%] | PD [%] caused by | | |
| | | | | vertical air temperature difference | warm or cool floor | radiant asymmetry |
| A | <6 | -0.2<PMV<+0.2 | <10 | <3 | <10 | <5 |
| B | <10 | -0.5<PMV<+0.5 | <20 | <5 | <10 | <5 |
| C | <15 | -0.7<PMV<+0.7 | <30 | <10 | <15 | <10 |

The operative temperature, $t_o$, is defined as the uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation and convection as in the actual non-uniform environment. The optimal operative temperature in a room can be expressed as a function of the activity and clothing. For a given space, an optimum operative temperature corresponding to PMV=0, depending on the activity and the clothing of the occupants is defined based on [89] (Figure 10). For additional information on the optimal operative temperature for the three comfort categories (Table 16), the reader is referred to ISO 7730-2005 [89].

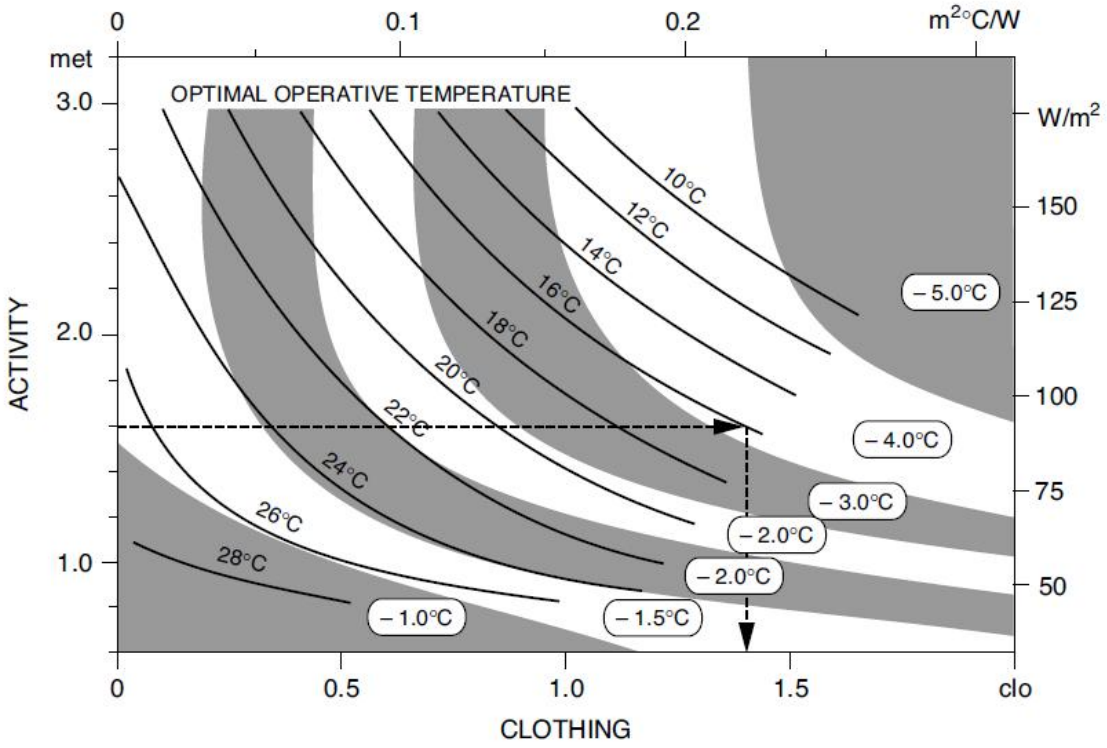



Figure 10: Optimal operative temperature as a function of the activity and clothing.

## 7.1.7. Alternative Methods

Other methods for the assessment of moderate thermal environments include the new effective temperature (ET) and the standard effective temperature (SET) [85]. These indices are based on a simple model of the human body. Today, advanced models are available that

allow for the transient prediction of very detailed thermoregulatory parameters and, for some of the models, subjective responses to a wide range of environmental conditions [86].

For non-air-conditioned buildings, an adaptive model has been proposed that determines the neutral temperature indoors based on the monthly average temperature outdoors. Over the years, several thermal comfort models have been developed that include human adaptability, for instance by Auliciems [94]. The concept of adaptive thermal comfort can be described as: When a change occurs causing thermal discomfort, people react in such a way that their thermal comfort is re-established [95]. This description refers to behavioural adaptation that can be discerned in personal, technical, environmental, cultural and organizational adaptation.

Physiological adaptation or acclimatization does not seem to affect people's neutralities, but there is some evidence that the acceptability is altered. Psychological adaptation implies a changed perception of (or response to) sensory information. Thermal sensations are influenced by an individual's experiences and expectations in a direct way.

Adaptive model s of comfort take human's adaptation to thermal comfort in such a way into account that warm indoor climates, which would be regarded as uncomfortable in air-conditioned buildings, are actually acceptable to the occupants of naturally ventilated buildings. Focusing on the performance indicators, which serve as a basis for the adaptive thermal comfort models, the main performance indicator is the operative temperature in the building.

Designing for natural ventilation became permissible across a vastly increased range of climate zones in 2004 with the incorporation of an adaptive model into ASHRAE's comfort standard [79]. This mainstreaming of adaptive comfort was further reinforced with the introduction in 2007 of a European standard (EN 15251) that closely followed the ASHRAE standard [79] precedent. Despite this broad international acceptance, there remains a gap in the theoretical underpinnings of adaptive comfort. Recent research [96] showed that discrepancies between the thermal comfort regarding the conventional HVAC setting and the naturally ventilated setting have been observed [97]. Especially, the experience of air movement as an unpleasant draft under one set of conditions, which induces pleasant sensations under different thermal conditions, has been an issue of interest. In addition, other researchers, for example [98], concluded that productivity effects of higher temperatures, perception of thermal comfort and indoor air quality should be subject for further research.

For additional information on adaptive thermal comfort in buildings, the reader is referred to Nicol and Humphreys (2010).

## 7.2. Conclusion

The analysis showed that the thermal comfort in a building is determined by the influence of the indoor environmental parameters on human's thermal sensation. Thermal comfort assessment includes a part of unambiguously defined performance indicators (PI) based on the notion of objectively quantifiable performance measures. The set of indicators is founded on existing knowledge in biophysics and physiology. The Core Indicator Thermal Comfort is characterized by five Performance Indicators:

- Operative temperature
- Percentage of Dissatisfied (PPD)
- Draught
- Vertical air temperature differences
- Radiant asymmetry

Each Performance Indicator is dependent of the specific indicators or parameters. Table 17 presents the performance indicators and related indicators/parameters for thermal comfort.

Table 17: Thermal comfort

| Performance Indicator | Indicator/Parameter | Description |
|---|---|---|
| Operative temperature | $t_o$ | Operative temperature |
| Percentage of Dissatisfied (PPD) | $t_a$ | Air temperature |
| | $t_r$ | Mean radiant temperature |
| | $v_a$ | Air velocity |
| | $p_a$ | partial water vapour pressure |
| Draught | DR | Percentage of people dissatisfied by draught |
| Vertical air temperature differences | PD | Percentage of people dissatisfied by vertical air temperature differences |
| Radiant asymmetry | PD | Percentage of people dissatisfied by radiant asymmetry |

# 8. CONCLUSION

In this report, a review of health and comfort related to acoustic comfort, visual comfort, indoor air quality, quality of drinking water, and thermal comfort has been provided. The indicators have been reviewed focusing on the implementation in an indicator framework for building performance assessment.

A summary of the earlier work, mainly within EU-projects, on performance based building and performance indicators for the indoor environment has been presented. A general definition of a (core) performance indicator was defined. It has been demonstrated that a core performance indicator can be described by a set of indicators or parameters. Each indicator or parameter can be assessed qualitatively or quantitatively. Target values describe specific guidelines with respect to each indicator/parameter.

Performance indicators related to the indoor environment have been reviewed. An analysis of existing and missing indicators has been performed. Performance indicators for the acoustic comfort, visual comfort, indoor air quality, quality of drinking water, and thermal comfort in a building have been presented. For each performance indicator, specific indicators, parameters, and target values are documented.

The study showed that the level of detail on which the information for the assessment of a building is available, is the main issue that influences the complexity of the indicator framework. Often, a specific indicator can be assessed on a global level, based on a qualitative and more subjective evaluation of the performance indicators, or a more detailed level, based on a quantitative and objective evaluation. While questionnaires and checklists showed to be suitable assessment methods for the first approach, detailed measurement of the performance indicators and corresponding parameters are recommended for a second more thorough approach. Focusing on the development of an indicator framework it is recommended to apply such a distinction (global vs. detailed) within the PERFECTION project.

The indicator lists which are presented in this report serve as an input for PERFECTION Subtask T1.5, which intends to develop a generic framework for core building performance indicators. The framework could be applied in different phases of the life cycle of a building, such as the design process, the construction, and the in-use phase. In each phase, different assessment methods can be applied for the evaluation of the (core) performance indicators.

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